Abstract

This publication describes a smart industry testbed for digital, connected and adaptive production machines and production chains. The testbed provides an architecture in which all data sources and tools are interrelated and share a common environment to research, develop, test and evaluate solutions in a synthetic environment. The testbed allows for real-time adaptability of machines and process chains to specific events (bottle necks, customer needs, machine break down etc.), while incorporating what-if analyses, creating intelligent products up to visualizing consequences of decisions. This can be used for the evaluation of alternative process chains for optimal lead time, manufacturing costs and quality. The testbed is not limited to a predefined use condition and copes with ever changing environments and users, and facilitates remote, inter-collaborative product development, support and maintenance through e.g AR/VR.

Keywords: Synthetic environments; Digital twin; Testbed; Industry 4.0

1. Introduction

Industry 4.0 (I4.0) challenges many companies to move towards a digitalized and connected manufacturing landscape [1]. Many possible advantages can be recognized after successful implementation, but this resulting effect is not always clear - and often impossible to communicate - throughout the implantation process. Furthermore, the effects (and thereby the involved risks) of making changes to an existing production environment are difficult to predict. Modernisation and changes in manufacturing companies are easier to accomplish if the consequences of change are known, and if it is always possible to look more than one step ahead. Having a clear, understandable and underpinned sequence of actions lowers the threshold for change and increases the obstinacy to change. A need in industry is visible to support and facilitate the decision-making process regarding connected and adaptive production machines and production chains, not only for the perspective of implementation, but also for the perspective of development.

Another motivator for developing an adaptable decision-making support environment is to provide structure to manufacturing industry to change to mass personalisation. This is often seen as one of the major prospects from I4.0 and does not only require flexible machinery, but especially requires a connected manufacturing process. A change has to be made from rigid product definition and thus inflexible process chains to interdependent data and production machinery. Manufacturing processes already shifted towards a highly digital environment, and during all the different lifecycle phases a lot data is produced. Nevertheless, many of the different phases in a product life cycle rely only on data generated for that specific purpose and maintain own data structures and working methods. Many advantages can be realized if throughout all phases all the data is available and usable, this ranges from incorporating what-if analyses, creating intelligent products up to visualizing consequences of decisions.

The extensive integration of online and offline elements of production lead to an environment in which physical and virtual elements of production are completely intertwined. A great
challenge in 4.0 is the optimal use of combinations between real environments and simulated (virtual) environments [2]. These environments are considered Synthetic Environments (SE). The use of an SE as design environment bring together real and virtual components to allow for adequately experiencing shared information [3]. They range from small setups, representing e.g. working with a new machine, to large systems for the conjoint development of new production facilities. This artificial environment represents an alternative reality, which acts as commensurable to a real environment as required. This alternative reality combines both real and simulated data and allow for various stakeholders to interact with it using virtual and augmented reality techniques. Understanding and knowing the relation and interdependencies between different assets is of great value to make optimal use of the possibilities, and to be able to assess vulnerabilities. The location and distance between different assets become less important, but an adequate matching of technology and design becomes more important.

The link between real and virtual is clearly visible in any digital twin (DT) [4-6], and shows great potential for real time monitoring, control and adaptivity in production. The realisation of digital twins often results in developing many digital connectors (e.g. interfaces) between single assets. This can be resources intensive work and has the risk to require high adaptation costs if something changes. It can become expensive and time-consuming due to its high complexity and the need for customised solutions. This is caused by the need to integrate many different hard- and software systems. Most often, these systems have their own way to exchange data in different formats via different protocols, which creates a highly unclear information density. Any supporting environment should prevent making connectors between each individual element but should offer a more sophisticated approach.

Reducing machine time and machine costs is one of most obvious goals to improve the efficiency of a manufacturing environment. This can only be done if it is known what leads to a certain machine time and costs, which of these parameters can be changes, what the alternatives are and what the effects of changes are to the complete manufacturing environment. Furthermore, evaluation of alternative process chains for optimal lead time, manufacturing costs and quality creates significant economic and environmental benefits. Support is desired to deal with this environments’ unpredictability, uncertainty and risks of change.

2. Prognosing manufacturing environment

To realize an environment to support the research and development to digital, connected and adaptive manufacturing environment, a ‘Smart Industry Testbed’ is developed. This testbed allows for evaluation of alternative process chains for optimal lead time, manufacturing costs and quality in the application area of this testbed is interconnected, adaptive production machines and production chains. This smart industry testbed allows to research, develop, test and evaluate solutions in a synthetic environment. The testbed provides an environment in which all data sources and tools are interrelated and share a common environment. Real-time adaptability of machines and process chains to specific events (bottle necks, customer needs, machine break down etc.) is an essential part in this research in order to make this testbed a successful fundament for industrial partners. The main benefit of the testbed is that existing real production environments can be virtually extended with machinery that is not available or purchased yet. The resulting combination of real and simulated assets forms an envisaged manufacturing environment where the effects of changes to the real environment can be tested. The testbed enables a fully automated factory – the total number of connected devices can be combined and managed as one ecosystem. In literature already multiple testbed environment can be distinguished, all with their own focus and perspective [7, 8]. Most of these testbeds limit the use and application area by predefining one perspective, or by focusing on a single type of production environment, this should be prevented.

The testbed is based on a shared data repository, every perspective of product development adds information to this repository, which eventually lead to a final design. This information driven design support [9] allows for a shareable and documented rationale of the current state of the design. In the testbed it is also relevant to make alterations to the data to review different perspectives, but with the possibility to get back to a previous state. This should not lead to having an ‘undo’ function, but to a situation where also the failed attempts should remain stored because they also contain relevant information. This information can be for example useful in other project with similar configurations or goals. This is the fundament for reusing data by making it meaningful through contextualising it in a testbed environment. By integrating all the available information in a combined digital and virtual testbed, different stakeholders can review the resulting configuration from their personal perspective and expertise. Missing information can be more easily traced with this, due to the lack of the need of one all-knowing person.

The testbed should represent the configuration of an envisaged potential reality. This allows to prognose the ability of single processes (quality, time, costs) in the context of the whole environment. This can be used as means to express capabilities. To understand the capabilities of a manufacturing environment - both existing and envisages - different production routes can be examined and reviewed. The production environment can be visualized in a roadmap style; where the route of every product throughout the factory can be visualized comparable to a visualizing a route for travel navigation by e.g. Google Maps, see figure 1. When multiple comparable machines are available, or when the sequence of
production of a product can vary, roadmapping the potential solution paths can give an indication about the flexibility of the manufacturing environment. When a bottleneck occurs – comparable to a traffic jam – on beforehand the production sequence of the succeeding products can be altered according to that. With available history data or with what-if analysis bottlenecks can be predicted. This information can be used to get insight in how to optimize the environment and to know when, where and what to extend or change in the future. This makes an environments’ unpredictability, uncertainty and risks of change instrumental for developers.

To communicate the configured manufacturing environment, the use of virtual dashboards [10] is an inherent part of the testbed. These virtual dashboards are visual representations and interfaces of parts of the available data. These can range from a digital dashboard with real-time production data from a single machine, till full blown 3D environments that allow for virtual reality supported training in an envisaged factory. The virtual dashboards enable the interaction with virtual and real machines, whereby the user is not always aware whether the changes are made to a virtual or real machine. The operator can be provided with the same user interface as the real machine, not influenced by a certain physical distance. With the use of virtual and augmented reality techniques the barrier between real and virtual can be removed and the interface of connected machinery can be operated over distance. By filtering the data, reviewing the consequences of interactions performed on the manufacturing environment can be assessed from different perspectives, depending on the expertise and background of the stakeholder. By integrating simulations and calculations in the combined real and virtual environment, the results of these what-if analyses can be contextualized by visualizing them in the actual representation of the environment, tailored to the most appropriate visualization for every individual stakeholder.

In figure 2 a representation of such a virtual environment is visible, in this example an existing factory is extended with simulated machinery (A) and even with non-existing tools visualized as a ‘black box’ (B). These imaginary machines are used to review the impact of a new machine if it would be possible to make it. In this case only the input and output of the new machine are determined, but the (real-time) input and output data of existing machines is utilized to simulate a realistic environment.

An economic value of having a testbed is to decrease the rework rate by being able to monitor continuously the current state of a produced product, quality control is integrated into the production process. Any recognised deviations in the product can lead to a direct change in production; this can be done by stopping, localizing and describing defects to initiate rework or by prematurely removing the product from the production process to save resources. Adjust the process in motion results in defect free production and in waste reduction. Even predictive and prescriptive maintenance can be part of the simulated environment of the testbed [11]. Figure 3 shows the goals of the testbed regarding prognosing the characteristics of a manufacturing environment.

3. Testbed framework

The testbed is not limited to a predefined use condition, it should cope with ever changing environments and users. Hence, the testbed supports the current challenges for digital, connected and adaptive production machines and production chains. The testbed allows for remote, inter-collaborative product development, support and maintenance (e.g. through AR/VR) which creates significant economic and environmental benefits. In order to realize this a framework is needed that supports the development of the testbed in such a way that it can deal with an ever-changing configuration of elements that form the future manufacturing environment. Besides this flexibility, reusability of parts of the testbed is supported. A framework should provide guidance to come to a robust and adaptable testbed.

3.1 Working towards intelligence

The reference framework is based on the RAMI 4.0 model [12]. The model developed consists of six nodes (dimensions) that work in a network without a predetermined hierarchy, see figure 4. These nodes represent different perspectives on the value of a testbed environment. The lack of hierarchy is essential since the development and information flows are not on beforehand a linear process, and value can be added from multiple perspectives at the same moment. Any smart industry testbed project can be initiated from every node and decision making is based on the coherence between multiple nodes. A node categorizes in its phase, function and position relevant to other nodes. The nodes provide a structure in shaping the framework and enables the development of an overview on where every element plays an (at first) equally important role.
Business

This node is responsible for the business strategy, goals and environment. It uses the elements of Industry 4.0 to support decision making and management.

Functional

The functional node is used for all output processes, actions, responses and functions for system control described in the framework. The functional node is executive and can be service-related.

Information

All stored and processed information that can be interpreted by human or machine is held in this node. The information exists in a digital form and is software-based. What data is used for the process and where does the data come from, are questions to be answered in this node.

Communication

It sets the communication standards and protocols used within the framework. It is the link between all elements playing a role in the process (and therefore testbed). It defines the networks that need to be used and how all elements in the manufacturing environment are connected.

Integration

The integration layer is the link between the physical world and the digital world. Converting all relevant data from the physical environment into a digital form. Allowing the data to be communicated throughout the architecture and used for further analysis and management.

Asset

The asset node contains all physical tools used for the development and processes of a smart manufacturing environment.

3.2 Building blocks to make the testbed instrumental

Rather than a prescriptive guideline, figure 3 aids to identify a generic system framework in collaboration with client companies and other related stakeholders. It raises the comprehensibility of Industry 4.0 practices, by explicitly taking into consideration the different perspectives it has influence on. To make the generic outline instrumental, a conversion is needed to define a set of working tools to form a functional testbed.

A common denominator in various manufacturing environments, and thus testbeds, is the fact that from every element that composes the environment multiple variants and options are available. This starts with having multiple machine options, due to varying manufactures and specifications. But also, multiple stakeholders will have different interests and decision-making mandate. In connected environments even multiple locations have to be integrated, which could be physically or digitally separated. Eventually in a working testbed environment also multiple timescales will be available, reaching from the historical situation, the current situation and the multiple future situations.

Based on the generic outline, building blocks can be identified that will build up to a complete testbed. The building blocks can be seen in figure 5. Depending on the process/manufacturing requirements, different building blocks can be used to develop a customised structure that functions as a guideline for the integration of Industry 4.0. Each block has its purpose and characteristics within the architecture. Depending on the blocks that are required for the design of the process, different subjects need to be considered. Each consideration comes with restrictions, opportunities and requirements that have an influence on the structure. Blocks will be added over time, and/or further specified. Furthermore, different variants of building blocks will exist, that can provide similar functionality but with the use of different tools.

Physical entity

A physical entity describes a product which exists in the real world. An entity can be monitored and can be used to act on the process. The physical entity can be a machine, product or another tool that is used or produced. Sensors and/or actuators are required to interact with physical products. A connection with a physical product allows it to be a part of the manufacturing network. This makes it possible to automate, analyse and manage these entities. The connection with these physical entities enlarges the scope of possibilities for improvement. A human that is participating in a manufacturing process can also be defined as a physical entity if s/he functions as monitor, actor or analyst. In this case, there is a need for an interface and there is no need for data conversion as the data is interpreted by the human and placed into the process in an already digital form.

Digital entity

A digital entity is a virtual product which is either a projection of a physical entity or a new design which can be tested virtually. It is a product that has a function in the digital environment of the process and differs for every perspective the entity is used. For the use of digital entities, there is no need for sensors or data conversion since the data which is generated is already in a digital form. A 3d model (e.g. CAD) of a product is an example of a digital entity and serves a specific perspective of the digital product.
Software
For a software-based entity, there is a need for common communication and integration with multiple systems. Software is used for data collection, transfer, analysis and interaction etc. It allows different stakeholders to be part of the process. Software applications that are used during product development, production and for management purposes are all software-based entities.

Sensor
A sensor is used to measure parameters and monitor physical entities. It makes it possible to collect raw data from the process and its environment. This block is in direct contact with the physical environment and is crucial as an input for the rest of the framework. It is crucial because it is the foundation on which the data-driven 14.0 is built. Therefore, it is important to realise what data is collected, why it is collected, and what degrees of freedom the sensors provide.

Data conversion
The conversion of raw data into a digital form is required for the processing of data and information. Data conversion is needed when there is a form of raw data which needs to be interpreted by a human or a machine.

Data storage
There is a need for data storage when historical data or data from other resources are relevant to the process. Depending on the functionality, one could think of local databases, network attached databases or cloud databases. Important to understand is the type of data and/or information that needs to be stored and where does the data come from and where does it have to go.

Communication
This block ensures the connection between all elements within the architecture. It describes the communication protocols needed for a fluent process. There are a few elements that need to be considered while integrating the block communication. Depending on what must be monitored, tracked or processed the communication is either wired or wireless. The speed, latency and bandwidth of the transfer of data and information are other aspects that needs to be considered.

Interface
An interface allows humans and machines to have an interaction and transfer information. There are three interfaces that can be used.
1. Human to human, which allows humans to interact and communicate with each other.
2. Human to machine, which refers to any interaction with a machine and a human (HMIs).
3. Machine to machine, which enables machines to work together in the manufacturing environment.

Intelligence
The integration of simulation, what-if analyses, Internet of Things (IoT), Cyber-Physical System (CPS) and other smart applications are determined in the intelligence block. Although this block is not used to build the customised architecture it does describe the overarching smartness that needs to be configured in order to improve towards 14.0. For the implementation of intelligence (e.g. data analytics), also the expertise of the human resources is utilized.

4. Testbed implementation
The testbed should be used as a working tool to get more insight in current and future manufacturing environments. The implementation of different building blocks into one consolidated environment is what forms the testbed. A combination of building blocks determines the eventual configuration and possibilities of the testbed. For each building block different variants will be available inside the blocks and based on the desired configuration a composition of blocks will be made. This also allows for interchanging the different variants of building blocks throughout the use of the testbed. Updating or changing the building block is possible without hindering the use of the testbed, or even without noticing the users.

4.1 Scaling of architecture
The level in which the blocks are placed can differ per case. In the case that the architecture defines the structure within one factory, an entity might be a machine. If there is a need for an architecture that covers a fleet of factories that collaborate, one factory may be defined as an entity. An entity can either be a machine or a factory depending on the level in which the architecture is built. In most cases, this would be relevant for the business node, but it shows that the level in which the architecture is built matters for the integration of multiple systems. It should be clear in which level the architecture is built and how the blocks are defined.

The digital system reference [10] provides guidance in the critical view on determining what should be known (e.g. measured or simulated) and at what moment, in order to make decisions. The testbed will form the integration of this and allows for a grading scale of quality; the level of accuracy and resolution depends on the use of it. The testbed also allows to embed real where required and virtual where possible.

4.2 Case
To fully understand the possibilities and capabilities of the testbed, the functionality of the testbed is described in the form of a case. In this case two machines on two different physical locations are connected in one shared environment, in combination with a virtual entity. The virtual factory thus contains three machines that are threatened as if they are physically in the same location. Figure 6 illustrates the different machines, their connectivity within the production environment and how it could fit within the reference environment.

Fig. 6. Structure of the demonstrator
framework. Both physical machines have connected sensors and actuators, and the simulated machine is treated the same.

The physical entity in Enschede consists of a three-axis CNC engraving machine, controlled via Arduino. Additional sensors are added to the machine to measure the position of the axes. This information is combined with a CAD model of the machine in a visual representation. This digital environment allows to control the machine and read the current status. All the acquired data is stored in the information backbone and can be accessed from every location. Additional IoT movement sensors are positioned in the area of the machine, and this movement data can be used to pause the machine operation if a human gets too close. There is no direct connection between this sensor and the machine, but all the information is stored in the information backbone and can be used by multiple applications. Subsequently, machine settings can be adjusted, and the data will be stored to determine the machine’s variation. An operator is able to supervise the processes with a software programme on a computer (figure 7) that is connected to the local database, or with the use of an AR device. The data from the information backbone is also used for a Manufacturing Execution System (MES), which on its turn is connected to the Enterprise Resource Planner (ERP).

5. Future vision

The smart industry testbed will always be in development and the architectures can change over time due to added functionality. The architecture will be considered the standard approach on how to configure a smart manufacturing environment. All entities that form the environment should be described in the building blocks; thus, resulting in only using machinery which is connected, and software that allows for flexible use conditions. The structure of such an architecture can strongly differ per case. Besides, multiple system architecture can offer the right solution for the same problem. For this reason, a case architecture should not be copied, but build from scratch from the building blocks.

The development of individual building blocks can be done by individuals without the need of constantly being connected to a working testbed. Companies can make their assets connected to enable the use in testbeds, without being hindered by taken into consideration all the possible connections to e.g. software platforms or cloud storage.

The flexibility of the testbed allows to use the same building blocks in multiple configurations. This makes it possible to integrate a physical machine in two different testbeds, without physically moving the machine. The machine can operate simultaneously in different virtual environment to gain insight in the effect of multiple configurations. Comparing the resulting quality of the environment (e.g. throughput, flexibility or maintainability) can provide support in the decision-making process towards most appropriate manufacturing environment.

6. Conclusion

The testbed, and the first demonstrator thereof, facilitate the decision-making process towards the realisation of a smart production environment. The general framework described in this publication supports the process toward realizing a testbed for digital, connected and adaptive production machines and production chains. The integration of all related elements in one synthetic environment results in a use condition that allows for adequate considerations between different options. These environments combine real and simulated information, and therefore allow for utilising multiple timescales, stakeholders, elements and locations to understand the impact of future manufacturing environments. This instrumentalizes an environments’ unpredictability, uncertainty and risks of change.

References