Applying digital twin technology in thermoplastic composites production

Supporting process monitoring, optimization and automation for real-time efficiency and smart quality control

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Abstract:
Many theoretical and practical challenges must be overcome in thermoplastic composites production. But what if digital technology could provide us the necessary insights to solve these challenges? An innovative out-of-autoclave production process is currently being developed in the Dutch regionally funded Luxovius project. The process involves integration of several production steps into a consolidated out-of-autoclave production process for assembled thermoplastic parts. By applying digital twin technology to this new production process, production waste, material usage, energy consumption and costs can be reduced during all phases from technology development to technology utilization.

Keywords: Digital Twin, Out-of-Autoclave, Thermoplastic Composites, Production Technologies, Machinery, Process Monitoring, Quality Control, Aerospace

Introduction

In the regionally funded Dutch Luxovius project, the Dutch leading supplier of technologically advanced aerospace systems and components GKN Fokker, the Dutch supplier of innovative thermoplastic composites production machines and automation systems Boikon B.V., the Royal Netherlands Aerospace Centre NLR and the Dutch University of Applied Sciences NHL Stenden join their know-how and efforts in developing an innovative out-of-autoclave process for the production of high-quality thermoplastic components; see Fig. 1. The process involves integration of several production steps into a consolidated out-of-autoclave production process for assembled thermoplastic parts. By applying digital twin technology to optimise this new production process, production waste, material usage, energy consumption and costs can be reduced during all phases from technology development to technology utilization.

The paper presents several views on application of digital twin technology in thermoplastic composites production. The collaboration amongst the Luxovius partners stimulates an interdisciplinary and cross-sector approach towards the development of a digital twin for thermoplastic composites machines. This approach will ultimately lead to a digital twin that covers the entire out-of-autoclave thermoplastic

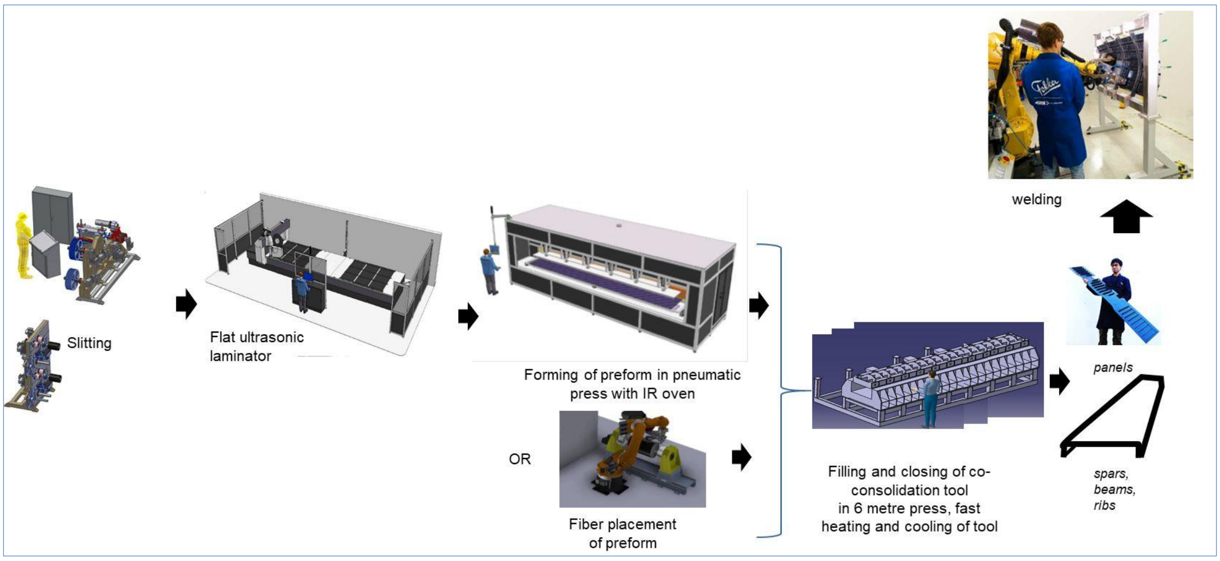

Fig. 1: *Process flow of the out-of-autoclave process (GKN Fokker)*

composite production process. The expected result is a practical and generic framework for digital twin development for educators, researchers, equipment manufacturers and producers of thermoplastic composites. We describe the notion of Digital Twin as used in the context of our research; the need to innovate the thermoplastic composites production process; the desire to optimise thermoplastic composites production machinery; the experiences in applying digital twin technology to existing production processes; and the wish to evolve a more holistic approach towards digital twin design.

Digital Twin

Many different notions of and definitions for 'Digital Twin' exist [1], [2], [3]. Most of the definitions are formulated from the perspective of the *application* of Digital Twin (DT) technology. According to Wikipedia, a DT is: 'a digital replica of a living or non-living physical entity'. In essence and without going in detail, a Digital Twin is a (near) real-time digital representation of a physical entity, such as a system, a device, a process, a product, a person, an animal, a crowd or a combination thereof. The digital twin uses data collected from, and information about, its physical twin, and applies a combination of information technologies, such as simulation, data science and machine learning, to form an accurate digital representation of its physical twin. The digital twin mimics the behaviour and properties of the physical twin during operation, facilitating analysis and optimisation of the physical entity, both online and offline. It provides its users with tailored interfaces to facilitate easy, end-user oriented interaction.

In the context of the research described in this paper, the envisaged DT is a digital replica of the Out-of-Autoclave (OOA) process. The research will focus on the development of a generic DT framework and the application of this framework for a DT for the OOA process. The framework will be used for developing a DT for the Automated Tape Layering (ATL) process.

The DT for the OOA process serves the following process management and control purposes:

- Monitoring and timely identification of deviations in processes and products on the basis of data collected from the physical twin during operation. This allows for optimal intervention and adjustment of the process, and also makes condition-based (i.e., based on data) predictive maintenance possible.
- Conducting performance analyses on individual process steps as well as on the whole OOA process. This facilitates process optimisation and real-time insights into the performance of the OOA installation.

Thermoplastic composites production

Since the 1990s, GKN Fokker has pioneered and industrialised thermoplastic composite processing, starting with stamp forming and then progressing on to consolidation of parts and the welding of assemblies. These technologies are highly automated, although part of the process, e.g. the lay-up of broad width fabric prepregs, remains a manual process. The level of automation is now increasing since thermoplastics technology is moving from being fabric based to being unidirectional (UD) tape based. UD tape lends itself well to fully automated deposition, in both 2D as well as 3D. All steps in the production flow are now becoming automated, supported by DT technology.

Holistic approach for Digital Twin stakeholder engagement and requirements distillation

From an end user perspective, the DT can be seen as an information system able to provide the right information in the right format at the right moment and the right place to the right user. To address human aspects such as the users' information needs, one must also include an understanding of the workplace culture in order to successfully develop and implement a DT for manufacturing plants.

A DT is a data model that contains information which should be of use for the end user. Therefore, the process of developing a DT can be seen as solving an information problem which end users face in making decisions that are based on information. To help solve these information problems, several information-seeking models have been developed [6].

Information-seeking models aim to describe the process that a user follows to satisfy his information need, and while fulfilling that need, the approaches toward formal and informal information sources or available services that finally results in success or failure to retrieve the desired information [7].

The aim of the first stage of the Luxovius project was to derive relevant DT use cases by engaging stakeholders in an early design phase.

The information-seeking behaviour model of Eisenberg and Berkowitz, popularly known as the "Big Six Model", is used as a framework and as interview guidance [6]. Multiple projected end users of DT within Fokker and Boikon – fifteen in total – in different positions in the value chain (operations, R&D, engineering) and at various management

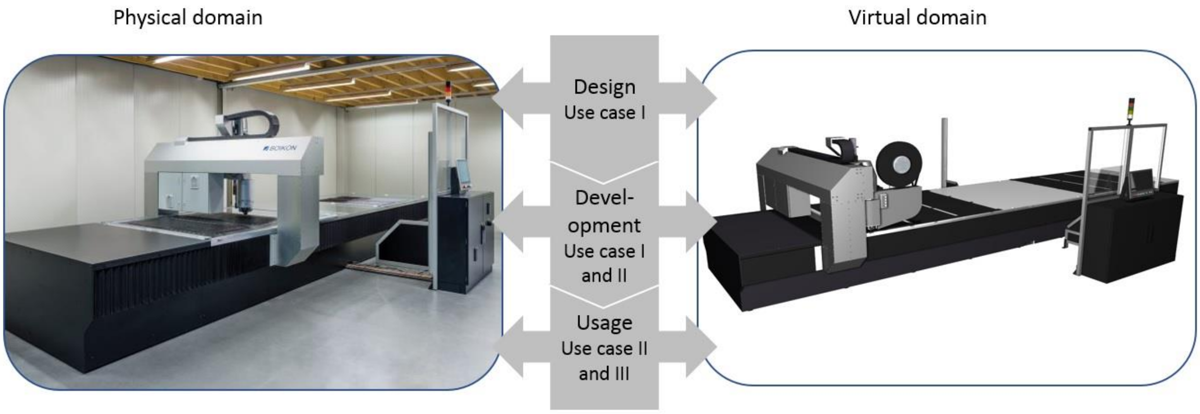

Fig. 2: *The use cases positioned in the value chain of the ATL machine.*

levels, participated in the interviews. Each interview was semi-structured and lasted two hours.

The following DT-related themes emerged from the interviews: measurement (1), data logging (2) and product registration (3) are conditional for monitoring (4) and data analytics (5). Based on this input, data-driven maintenance (6) and simulation models (7) can be developed and validated.

The interviewed stakeholders within both Boikon and Fokker are involved in the entire value chain: from design, to manufacturing, to end use. Based on the interviews, two general DT use cases and one specific use case emerged; see Fig. 2. The general use cases are related to data-driven design and data-driven maintenance, and concern the design and service phases of the machine with the aid of simulations and historical data. The specific use case is related to the ATL machine, in particular to health monitoring of the sonotrode. The general use cases concern monitoring and data analysis, whereby the DT enables both process optimisation and quality improvement. The specific use case is related to data-driven maintenance, where a DT enables condition-based maintenance based on the intensity of the machine's actual use during operation, and the kind of operations it is tasked to perform.

The projected aims, input and output parameters of the DT, access constraints, and suggestions regarding visual representation of data were summarised with the aid of the mutual stakeholders' responses.

Thermoplastic composites production machinery

The methodology as described in the previous section resulted in the three following use cases, which will be demonstrated with the Falko ATL machine of Boikon:
I. Data-driven design
II. Real-time monitoring and data analysis
III. Data-driven maintenance

The multi-disciplinary and multi-sectoral approach showed two interrelated results: on the one hand, use cases that relate to the production machine builder; and on the other hand, use cases that relate to the OOA production process in which the production machines are actually used.

I. Data-driven design
Data-driven design refers to using data to reach and maintain the optimally attainable efficiency level, all the way from initial development to long-term field service of production machinery. Research indicates that the root causes of long lead times typically occur in the product design phase [4]. Furthermore 75-80% of avoidable costs is controllable at this stage [5], making this specific use case of great value for machine builders.

During the design and development phase no physical machine may yet exist, in seeming contradiction to the given definition of a DT always requiring a physical twin (PT). However, this phase is especially valuable for machine builders. Using DT technology based on a virtual PT (as represented in for instance CAD) and related tools as monitoring, logging and analysis enables software control development and debugging prior to assembly of the physical machine, resulting in reduced lead times and better overall performance. Required mechanical functions or sensors can already be identified at this early stage of machine development, reducing rework or other unforeseen errors; see Fig. 3. The DT model is then verified and optimised using actual data provided by the physical twin, once it is built.

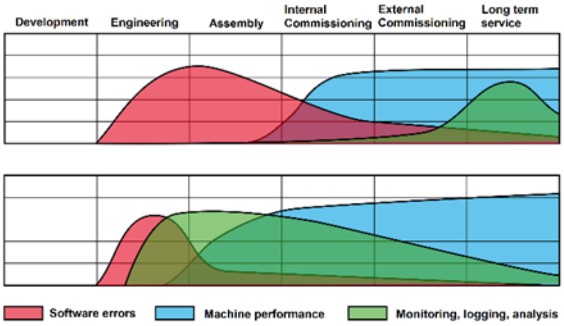

Fig. 3: *Diagrams of software errors, machine performance and monitoring, logging and analysis of data throughout the delivery phases of production machinery, without DT (upper diagram) and with DT (bottom diagram) (Boikon B.V.)*

II. Real-time monitoring and data analysis

Production machines turn materials into subpreforms or final products. Deviations may occur during production causing production errors, especially with new high-end processes such as the OOA production process, because material behaviour is not yet fully known or predictable. Some of these deviations can be traced directly to the raw material properties or supplier, and others can be traced to the production machinery used. More troublesome are deviations causing product rejects at latter stages of production that do not have any directly attributable cause. The cause of these rejects would remain unclear since the product already passed several processes and quality checks, and those quality checks are primarily based on potential defect sources that are already known.

Real-time logging of all data is essential to tackle this invisible issue. Analysis of the machine, process and even such other data as ambient conditions can reveal subtle trends that are normally hard to detect, but actually do influence the final product. Relevant data can be determined by means of data mining. The obtained data must be linked to the product, which becomes a digital passport of the physical product. By comparing and analysing the digital passports of approved and rejected products, models and predictions can be made to improve quality monitoring, thereby reducing the need for random sampling, driving down product rejection, and leading to optimal intervention and adjustment of the overall fabrication process.

III. Data-driven maintenance

Condition-based maintenance through data analysis has been applied for many years already. Therefore, this use case does not focus on general maintenance, but specifically on the wear of the ultrasonic end effector of the ATL machine. The results are valuable for the thermoplastic composites industry because weldability is one of the core cost-saving advantages of using thermoplastic composite material. Data-driven health monitoring and maintenance uses DT data to investigate which factors influence the wear of sonotrodes, with the ultimate goal of predicting the wear pattern during active use, over the tool's entire serviceable lifetime.

Ongoing experiences in a pilot plant

In 2015, NLR and GKN Fokker established a dedicated field lab at NLR premises in Marknesse, the Netherlands, for the automated production of composite aircraft parts; see Fig. 4. In this 'Automated Composite Manufacturing Pilot Plant' (ACM-PP), smart manufacturing technologies for high quality composites are developed, applied and assessed. The pilot plant is highly automated and is designed to be operated by a single operator. Automation and robotics obviously play prominent roles. An extensive network of sensors built into the plant produce a plethora of data, and are all managed automatically by the facilities in a way that makes operation by a single person feasible. In the context of this pilot plant, NLR investigates the application of DT technology for monitoring and optimisation of the manufacturing processes, starting with a Resin Transfer Moulding (RTM) process and an induction welding process.

DT technology in the ACM-PP is primarily foreseen to support intelligent monitoring of the optimal process window (including signalling and notifications for the operator) and to facilitate condition-based predictive maintenance based on extensive analysis of available sensor data. The DT technology serves to facilitate and ease the workload of operators, and must not result in more than a minimum extra effort for production job planners. In future, DT technology will help developing and optimising production processes.

Developments so far have resulted in prototypes that support the operator in monitoring the process at a higher level than merely collecting and displaying actual process values. The prototypes cover such aspects as:

- Interaction between the operational hardware and the DT software (i.e., integration of operational technology with information technology);
- Integration of job planning information in the automated monitoring process, through automated import of set points from the working instructions into the DT, and usage of those set points in automated checks;

- Data analysis on measured values to improve the identification and signalling of deviations with minimum false alarms; and
- Tailored, end-user oriented human-machine interfaces.

Fig. 4: *The Automated Composite Manufacturing Pilot Plant, showing the RTM facility at far left, an overbraiding facility at left centre, and a raw material pick & place and automated preforming facility at the right (NLR)*

Based on lessons learned during the development of the DTs for the ACM-PP and the Luxovius project, NLR is developing a generally applicable methodology for design and development of DTs for production machines and processes. This methodology aims to provide a framework and architecture guidelines and generic building blocks. The methodology also guides the development of a DT for particular use cases in terms of determining the DT's main purposes, stakeholders, needs, context, required user interaction, and available as well as required data and models, knowledge, information technologies, and integration of operational technology and information technology.

NLR is also extending its knowledge on application of DT technology to other domains, such as monitoring and condition-based maintenance of aircraft parts and aircraft, and fleet monitoring and maintenance.

Conclusions and way forward

Although the Luxovius project has only just started, the first stage of interviewing the stakeholders delivered three industrial use cases to be supported by future DT development in thermoplastic composites production. Two general use cases are *data-driven design* and *data-driven maintenance*. A third specific use case is *data-driven health monitoring for the ATL machine*.

The derived DT themes show striking similarity with the DT design dimensions found by Stark et al and described in their so-called Digital Twin 8-dimensional model [8]. Only the DT dimensions Human interaction and Cyber Physical Systems Intelligence were not strongly reflected by the interviews.

However, many processes are operator-driven due to procedures in aircraft industry. This means that the Human-Machine Interface (HMI) is a relevant design element.

Important lessons learned during the definition of the industrial use cases include:

- Having a common understanding of DT and the potentials of DT technology is essential for successful development of DTs;
- Focus on stakeholders' needs from the start: how (i.e., what for, and in what form) the stakeholders wish to use the DT and consider implementation details later. Also help stakeholders by raising awareness of the potentials of DT technology;
- Think big and develop a common vision by stakeholder engagement via a top down approach and define an ambitious DT, but start small, i.e. implementing bottom up by developing smaller DTs as part of the ambitious DT;
- Involve interdisciplinary specialists throughout the DT life cycle;
- Explore the context and the impact of the DT in the business organisation, early on in the DT development;
- Integrate DT technology in the digital transformation roadmap to accelerate adoption in the business DNA.

The next phase in the research is to develop a framework and architecture for application of DT technology in thermoplastic composites production machinery, and a DT model for the ATL machine. Preliminary results are expected to be available around the end of 2020, after which the use cases will be elaborated and intermediary results will be investigated. The first DT results are expected in 2021.

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