Towards a human-centric Digital Twin architecture for Industry 5.0: Aiding skilled operators with composites production automation

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Abstract. Industry 4.0 uses digitalization technologies to collect huge amounts of data during production processes. Digital twins can support processing, mastering, and exploiting the plethora of data to assist in optimizing production throughput [1]. But how can digital twins actually support skilled operators on the factory floor? In this paper, we present the design of an operator-centric digital twin for an automated composites production process from start to end, thereby exploring key elements of the architecture of the operator-tailored digital twin and exposing valuable lessons learned from the operator-centric design process. The development methodology applied, and the resultant digital twin architecture, show how operator-centric design guidelines are successfully translated into implementation. This approach helped transforming an otherwise straightforward Industry 4.0 implementation into a state-of-the-art Industry 5.0 implementation, wherein the digital twin plays a central role in supporting and assisting operator-based decision-making at the core of the production process [2].

1. Introduction

1.1. Vision for digital twin application within the context of RTM production

As part of the Advanced Composites Manufacturing Pilot Plant (ACM-PP) [3] established by the Royal Netherlands Aerospace Centre, a digital twin was developed for the resin transfer moulding (RTM) [4] process that is part of the production of complex composite aircraft components [5]. The ACM-PP is a cutting-edge research facility consisting of multiple semi-automated manufacturing stations, part of NLR's Fieldlab for Automated Composites and Metal Manufacturing and Maintenance (ACM^3) [6]. Within the ACM-PP, the RTM digital twin's role is to collate and analyse streams of raw data from several production machines into a focused overview of the overall RTM process, provide the operator with that overview to assist in monitoring crucial operational parameters, and suggest critical process adjustments with minimal distraction.

In order to learn how a digital twin can be optimized to assist operators in understanding and controlling complex production processes, operator experiences and human factors are used to drive the overall digital twin architecture and design requirements. This approach stems from the underlying observation that in many situations the operator is the process expert, has the expertise needed to optimize aspects such as process efficiency and product quality, and is ultimately responsible for the production process. So, instead of designing the digital twin to steer the process directly, it is mainly targeted towards providing the operator with useful and insightful information needed to optimally monitor and control the process. A fundamental guideline is to therefore continually ask the question: *How can the digital twin be used to actually help to empower the operator?*

This user-centric approach impacts the digital twin design process from start to finish, beginning with needs, requirements, and ideas capture, and is followed all the way through to implementation, testing, and evaluation during production, with the operator as key stakeholder of the final digital twin at every design step along the way. This results in a digital twin architecture that not only supports process management and oversight, but also adapts easily to evolving operator needs, and can be readily reconfigured and deployed for new composites manufacturing applications.

1.2. Fully automated RTM production process

The innovative production process for landing gear parts involves the stepwise production of fully automated lay-up fabrication and preforming, preform injection with thermoset resin under vacuum, curing, and final machining [7].

In RTM production, both injection and curing are done directly inside a mould designed to fit the preform. RTM production has the disadvantage that a customized mould has to be machined, but eliminates other drawbacks related to the traditional autoclave-based production process, by applying direct heat and pressure to the preform during curing inside the mould. RTM production furthermore improves overall geometric tolerances, and results in less material scrap.

Whereas an autoclave is a self-contained machine with built-in pressurization and heating capabilities for a fixed volume, and can accommodate any preform that fits inside the machine, in RTM production the pressurization and heating capabilities must be supplied by auxiliary apparatus external to, and to some extent also customized for, the specific preform mould. Several systems from different manufacturers must therefore be connected to the mould, and carefully monitored and coordinated during the injection and curing steps.

The RTM system at NLR’s ACM-PP is depicted in Figure 1. It consists of an RTM machine to heat and inject the resin (left), hot water lines from auxiliary water heaters (far left) to the injection mould (centre), and a press containing the mould (right).

Figure 1: The RTM facility at NLR's Advanced Composites Manufacturing Pilot Plant

1.3. Digital twin for RTM production

A digital twin is used to collect real-time data from the various RTM support systems, including mould pressure, temperature, and other readings, in order to provide a coordinated systems-level overview of the entire production process during injection and curing. The digital twin coordinates real-time logging of readings from multiple individual apparatus, presents process parameters in an easy-to-understand way for operators, and automates monitoring of critical process parameters during production.

The primary aim of the digital twin is to make it possible for the entire ACM-PP production process to be run by a single operator. It does that by monitoring and predicting the product quality at every stage of the production process, providing suggestions to the operator on how to optimize production performance. The digital twin warns the operator of any potentially deleterious trends affecting the product quality, and provides direct insight into the actual state of the preform during injection and curing. Data collected by the digital twin facilitates offline production process performance analysis and quality enhancement, makes it easy to review and analyse the influence of parameters in past production runs, and helps to develop more accurate models of the injection and curing processes.

The digital twin clearly embodies much more than just a supervisory control and data acquisition (SCADA) system, also performing model and data based process analysis in real-time, with the aim of easing the complexities of ACM-PP operation, detecting deviations from the modelled process and expected results, and helping the operator with a clear and coherent view of what process parameters are impacting product quality at any given moment in time.

In order to make that possible, numerous challenges were addressed during the design of the digital twin. Although entire commercial off-the-shelf (COTS) ecosystems exist to implement SCADA with custom software, NLR desired more flexibility and wanted to avoid single supplier lock-in, and be able to explore first-hand the key architectural elements comprising a digital twin, resulting in a custom setup.

One of the first challenges resulting from that approach was to access and unify data from machines supplied by different manufacturers including auxiliary equipment, such as the water heaters for warming up the mould, various sensors, as well as the RTM injection machine itself. Some of these have unpublished software interface descriptions and different data access protocols, so interaction with the manufacturers' engineers was necessary in order to successfully integrate some of these machines.

The next challenge was to develop a secure and service-oriented middleware including protocol and hardware abstraction layers. This approach keeps the digital twin interfacing flexible and future-proof. The interfacing incorporates several techniques supporting aspects such as standardized data formats, synchronized collation of data with timestamps from multiple sources having different sampling rates, active monitoring of all data-producing equipment for online status, data consistency, safe operating ranges, and data communication with high cybersecurity.

Our final and most important challenge was to implement an operator-centric digital twin interface for the RTM process operator, and to facilitate ongoing development of the online analysis capabilities of the digital twin in support of plugging in data science algorithms/modules/technology. Higher-level software architecture considerations therefore included aspects such as: automatically collating and presenting live data in an easy-to-understand format for operators; securely restricting data access to authorized local operators and remote stakeholders, without impacting ease-of-access by multiple simultaneous users; automatically parsing production recipes into machine-readable alarm levels; augmenting real-time data with metadata using AI algorithms; and making it possible to easily review and analyse both live and previous production runs.

2. Design and development of an operator-centric digital twin

2.1. Establishing requirements and defining a blueprint

In order to successfully implement the many different requirements for the digital twin, NLR developed a methodology for obtaining and translating stakeholder needs into a set of architectural requirements for the digital twin. The steps of this applied methodology are as follows. A more detailed description of the methodology can be found in [8].

1) Sketch the application context. This step includes identifying all relevant domain experts, agreeing on the overall role of the digital twin, expressing a vision of the anticipated digital twin's capabilities, and establishing a consistent technical and architectural terminology.

2) Specify the digital twin. This step involves demarcating the scope of the physical twin for which the digital twin should be made, by interviewing the stakeholders regarding their needs, desires, and expectations, defining the envisaged digital twin use cases and application scenarios, determining the digital twin's operational context (including interfaces with other systems and digital twins), and identifying any organizational constraints like security or intellectual property-related limitations.

3) Design, implement, and evaluate the digital twin, using well-established design methods. Here an architecture-based systems engineering paradigm is applied to establish: the main functions of the digital twin; functional requirements, attuned to stakeholders' needs; a logical component architecture able to support those functional requirements; an implementation-agnostic blueprint embodying the logical component architecture; and finally, a detailed physical architecture with component selections to implement the blueprint.

While following this methodology, it remains crucial to continually and iteratively account for active involvement of stakeholders at all stages of the operator interface design, an agile software development approach that promotes modular upgradeability, any relevant and applicable standards and norms regarding interoperability and communication, and the ability to build up along the way using simulation and emulation techniques like Software- and Hardware-in-the-Loop (SIL and HIL, respectively).

2.2. ACM-PP architecture and implementation

By following the established design methodology, and taking into account the various implementation considerations, gradually and ultimately a digital twin topology was developed as shown in Figure 2.

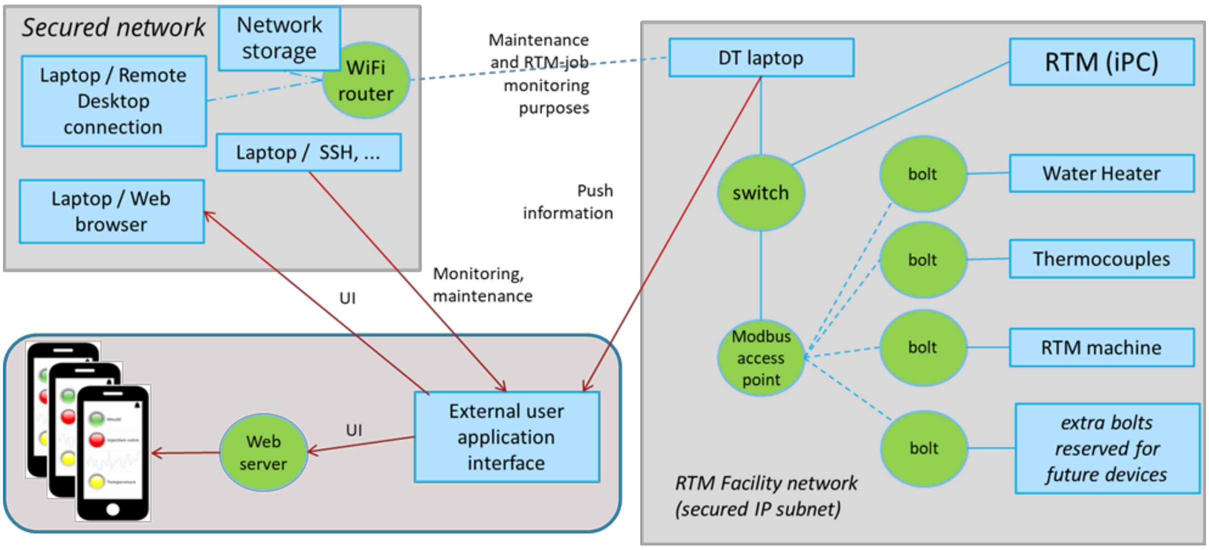

Figure 2: Overview of the digital twin topology

Several implementation aspects were considered during the transition from a blueprint to the actual implementation. A complete inventory of the required functional components, data sources, and data consumers was made, based on stakeholder interviews. This included a review of the necessary data acquisition, processing, storage, and data management and accessibility options. The stakeholder requirements also illuminated several key aspects such as: interoperability and communication with other systems, including other digital twins; ensuring easy (re)configurability of the digital twin; the ability to provide data analysis and component simulation/emulation capabilities, both online and offline; and foremost of course the design of data presentation and operator interface with a look-andfeel tuned and optimized for efficient and effective operator interaction. The resulting digital twin implementation embodies the following core components derived from the architectural requirements:

- Dedicated industrial PC
- Protocol-agnostic hardware abstraction layer
- Data analytics plugin
- Flexible configuration, with initial settings automatically imported from the work-instructions
- Digital twin logging, including prediction algorithm outputs and operator interactions
- A prominent and easy-to-read digital twin dashboard for operators
- Secure industrial network topology (including network firewalls and other measures)
- Secure Web server application
- Secured remote web client for handheld

Special care was taken during the digital twin design and development to present data clearly and facilitate operator interaction with the running production process. Specific arrangements were made that enable the operator to, amongst other things, scrobble through the time history of the production, bookmark critical moments in the production history for subsequent analysis, set, override, and adjust monitoring alarms (while all interactions are logged), and zoom into readings of specific interest at a detailed level. Also, remote stakeholders are enabled to follow production by remote access to the graphical user interface without the possibility to accidentally interfere or override and adjust alarms.

Secure connectivity of equipment and sensors to the digital twin computer had to be guaranteed, as well as secure access to the manufacturing data being collected. Keeping in mind the strict regulations that apply to the aircraft manufacturing industry, NLR had to make sure that all interactions with the digital twin can be independently assessed by the machine operators, using the digital twin to obtain a live picture of the running production process. Using these understandings, the operator can clearly see and steer the right process settings needed to obtain an optimum end result for the product.

The RTM setup with in-loco and handheld operator interfaces is shown in Figures 3 and 4.

Figure 3: Operator’s digital twin dashboard

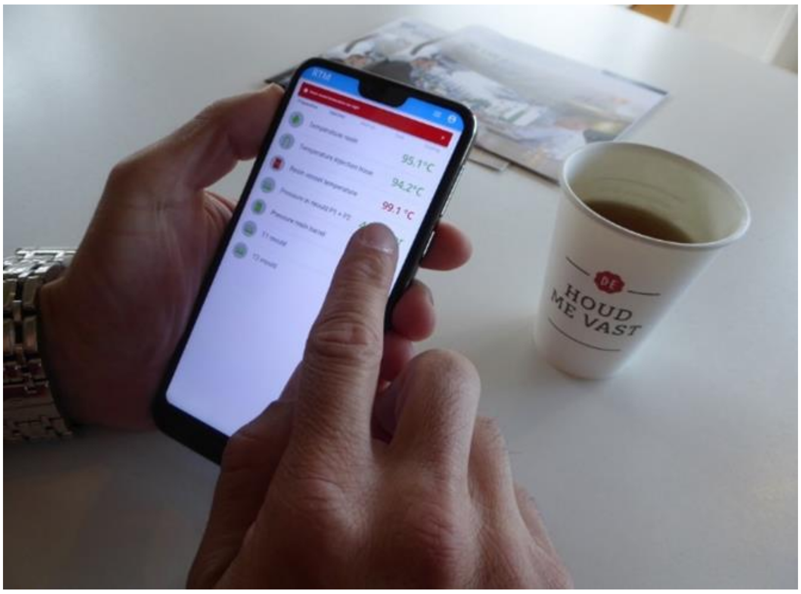

Figure 4: Operator’s remote handheld

Examples of some of the operator-centric features implemented are depicted in Figures 5 and 6.

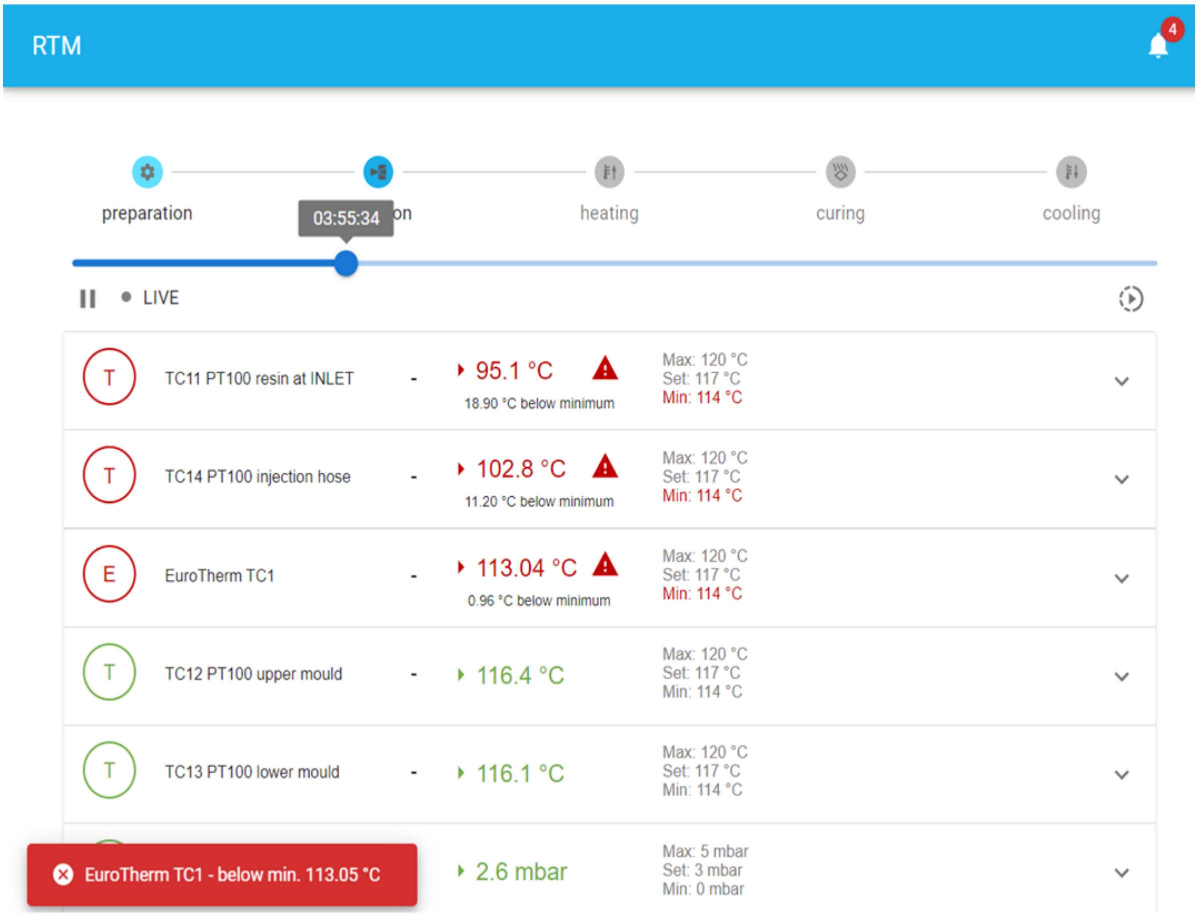

Figure 5: Monitoring with adjustable alarms

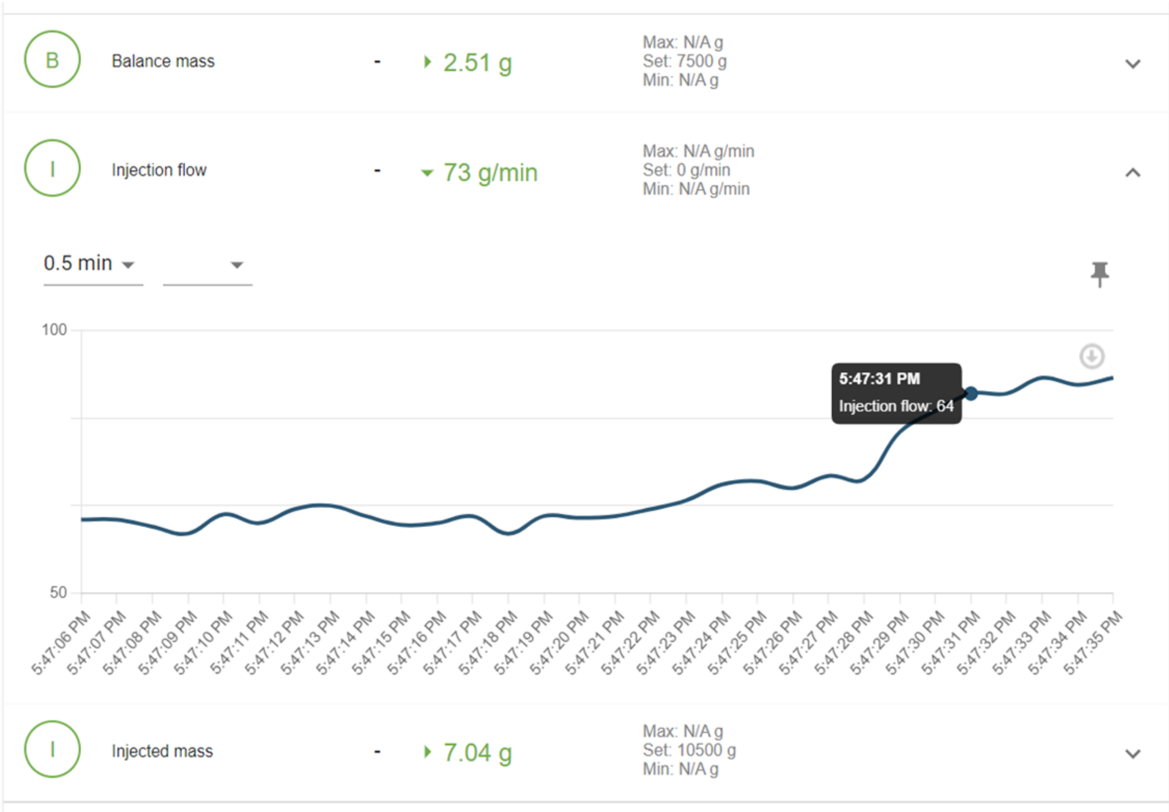

Figure 6: Production history scrobbling and bookmarking

The interactive graphical user interface is specifically designed to facilitate ACM-PP production by a single operator. The digital twin dashboard has a timeline at the top of the screen showing each phase of the production process and automatically detects and highlights the currently active production phase. It provides a count-down time to the anticipated transition to the next production phase, as well as the expected time of ultimate completion for the part being produced. The digital twin adapts the interface to the current phase of production, with the dashboard showing the most pertinent parameters on top of the screen, however the operator has the freedom to choose to drag and drop the monitored readings into a different order, or even pin them so they are always visible. Any monitored value can be tapped or clicked to obtain a drop-down graphic of the parameter's historical values, and the timeline can be expanded, contracted, and scrobbled backwards in time to examine parameter values of interest at specifically critical moments of interest. Bookmarks can be placed and annotated for offline inspection and review, and alarm levels can be dynamically adjusted based on operator insight. The interface is also accessible using handheld devices so the operator can still monitor operations while mobile, in order to inspect and adjust other parts of the ACM-PP process, or simply to take a coffee break. The digital twin employs data analysis algorithms to highlight process parameters that the operator might consider in order to optimize product quality. All operator interactions and alarms are logged to facilitate offline analysis of the production results and tweaks performed for optimization of subsequent production runs.

3. Conclusions

NLR took a step from Industry 4.0 to Industry 5.0 by designing and implementing a user-centric digital twin for NLR's RTM production facility, where the operator is a key stakeholder in the design and implementation of the digital twin. The digital twin provides live feedback to the operator to provide insight into what machine settings are currently affecting product quality. It can be used offline as well, to help operators analyse production results and explore potential future improvements leading to improved efficiency, fewer defects and less material waste.

For the fabrication of aerospace components at NLR, the RTM digital twin has proven its value as an indispensable tool for achieving better results and more efficient production, yielding valuable new insights into process optimization and maintenance activities that were previously elusive or even unobtainable. Since aerospace production applications require adherence to strict certification guidelines–which do not readily permit the introduction of automated alterations to established production processes–the introduction of a digital twin to aid aerospace component manufacturing to this day still requires a skilled human operator to act as the final decision-maker.

We have shown that it is not only possible, but extremely effective, to introduce a digital twin into new production processes by providing valuable assistance to the skilled operator, whilst remaining responsive to operator inputs, by developing the digital twin with the operator as a key stakeholder during the design process. The result is a digital twin that goes beyond Industry 4.0, towards Industry 5.0: the creation and introduction of innovative digitalization technologies aimed to help humans interact more pleasantly, fluidly, and effectively, with complex machinery and certified production processes.

The lessons learned from the ACM-PP RTM digital twin development were further leveraged for the design of digital twins elsewhere, such as in the Dutch Luxovius project [9].

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