DIGITAL TWIN FOR AGILE MANUFACTURING: CHALLENGES FROM THE OFFSHORE WIND TURBINE INDUSTRY

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ABSTRACT

This paper highlights technical and practical challenges that the authors have faced to create a digital twin (DT) of a piece of manufacturing system, that is production process (i.e., assembly process) to serve system responsiveness (i.e., agility) in an offshore wind turbine manufacturing. It discusses the elements and architectural parameters in development of an agile manufacturing system, where DT of shopfloor and its practical setup is seen as a design element enabling agility in an industrial system. Currently, there is no detailed framework to describe how industries can practically benefit a DT of their production process in a way that their manufacturing systems becomes responsive to perturbations, and ultimately agile. More importantly, there is no detailed study to show potential challenges and their implications during deployment of such a DT. In absence of such a study, this paper proposes a configuration and practical architecture, customized for Siemens Gamesa Renewable Energy's (SGRE's) offshore wind turbine (OWT) manufacturing system, that denotes the logic behind such framework for reuse of DT in any typical manufacturing system along with its practical implications, helping other industries to predict potential challenges and estimate realistically the required budget for such implementation. The proposed model-based structure is built up based on the benchmark commonalities and differences of the known developed DT models in manufacturing and production context, incorporating the existing physical and virtual spaces in SGRE's OWT manufacturing system, complemented by supplementary systems and software applications from existing technologies in market. The paper concludes with thoughts on a pilot project in production line of an OWT's generator unit that is under development to verify such a design.

DIGITAL TWIN IN MANUFACTURING – AN ENABLER FOR AGILE SYSTEMS

The digital twin (DT) concept revolves around the principle of mirroring and monitoring a physical asset's constitution and behaviours using a simulated counterpart (Fonseca and Gaspar, 2021). Both physical and virtual sides share the purpose of supporting decision-making during operations, either in (near) real-time or pre- emptively. The digital twin represents a tool for verification and validation of system behaviours, and the study and debugging of operational problems. After the aerospace sector put the digital twin forward (Shafto et al. 2010; Boschert and Rosen (2016)), it has been adopted by an array of other industries, including manufacturing.

Diverse conceptual schemes for DT are observed in the literature. Grieves (2011) defines a physical and virtual space connected by information flow across their elements. Kraft (2016) introduced digital thread as a standard that brings the *right* information to the *right* place at the *right* time with a focus on the virtual space, partitioning it into five interconnected models. Zhang *et al.* (2019) introduced digital twin-driven cyber-physical production system (CPPS) structured in five layers. These elaboration, however, remained at conceptual level for interested practitioners and companies.

Since then, data-driven applications, computerized systems, and technologies contributing to the concept in manufacturing system have been developing continually and interchangeably. Technologies such as virtual reality (VR) and augmented reality (AR) yet remain limited to simulation or virtual aspect of an object or a process. While the physical dimension of the model requires application of a complicated system engineering on interactions across sub-systems and the ultimate architecture of DT. Such an engineering is specially needed where the physical dimension of the model contains smart technologies, e. g., cobots (collaborative robots), smart devices enabled by PLCs for machine learning (ML), open platform communication unified architecture (OPC UA), supervisory control systems (such as SCADA), and live tracking and monitoring systems in the format of manufacturing execution systems (MES).

More specifically in manufacturing context and production processes, a more precise definition of a DT implies a real-time representation of the real-world (Leng *et al.,* 2019) by which the real-time visual remote monitoring, accurate prediction of analytics and future behaviours, optimization and validation of alternative

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scenarios, communication (feedback loop) and documentation are enabled. These functions in a digital-visual format, from one side integrated with product lifecycle management platforms (PLM) and from the other side integrated with digitized, robotized, and automized solutions at physical space, close a loop which serves agility and response steps in a coherent system design. In this context, the scheme from figure 1 helps to shape our understanding on how DT is a key enabler for an *agile* manufacturing system.

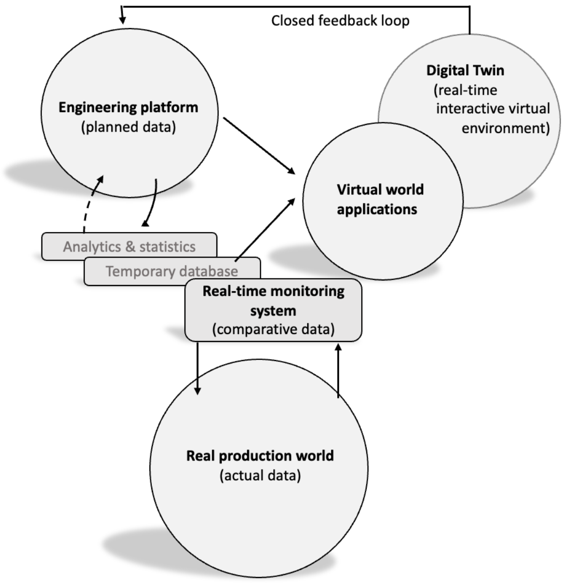

Figure 1 - An Agile System's High-level Design wherein the Closed Feedback Loop is Enabled by Production DT

Virtual world in figure 1, can have multiple versions, such as virtual real-time running production (fed by actual data) or virtual generic production (fed by planned data) or a virtual hybrid reality (fed by analytical and statistical data, usually aiming to represent an optimizatied version of real production). DT here is an environment in which a collection of systems, that represent the real-time running production in virtual format, collaborate in an interactive mode. The closed loop of the virtual world/DT and the engineering platform is simply recognizable in figure 1. However, the loop of the virtual world/DT and the real world is only closed through the engineering platform. That means, there is no direct data flow from the virtual world/DT to the real world, unless through the engineering platform that is the only authorized source of data to feed the real world. The validity of this fact, in both theory and practice, comes from the conceptual and practical differentiation between the virtual world and engineering platform that is pretty new for the history of indusytrial virtuality. Such differentiation has taken place by introduction of technologies, with capabilities of representation in both worlds, and digital interfaces of the reral-world (e.g., manufacturing execution systems (MES)). DT in agility design is meant to fill the gap between the real-world and the engineering platform.

Agility in manufacturing is here understood as a high-level responsiveness, that is, a property that enables the system to respond quickly and effectively to a change, regardless of predictability, or identifiability of the change. To be agile, a selection of system properties (referred to as *-ilities*) should be activated on right time, while interacting interchangeably, to detect the change, interpret and analyse the risk, make a decision, act and reconfigure the system according to the new status. There are technologies to provide physical and virtual solutions for each of these steps, where the response behaviour is the result of an integration of all these solutions in a way that sub-systems can talk to each other and collaborate interchangeably to cover alternative possibilities toward an optimum response as quick as possible. Thus, a DT and its practical setup seems to be the right element for converging these technologies in a manufacturing system whereby the collaboration of virtual and physical sub-systems is enabled. (Nickpasand and Gaspar, 2023)

In a review of literature and existing structures for real-time DT that are used in manufacturing, four architectures supported this paper. In all these architectures, up-to-date technologies and state-of-the-art solutions are utilized and validated in relevant experiments. Qi et al. (2021), Yi et al. (2021), Redelinghuys et al. (2020), and Zhang et al. (2019).

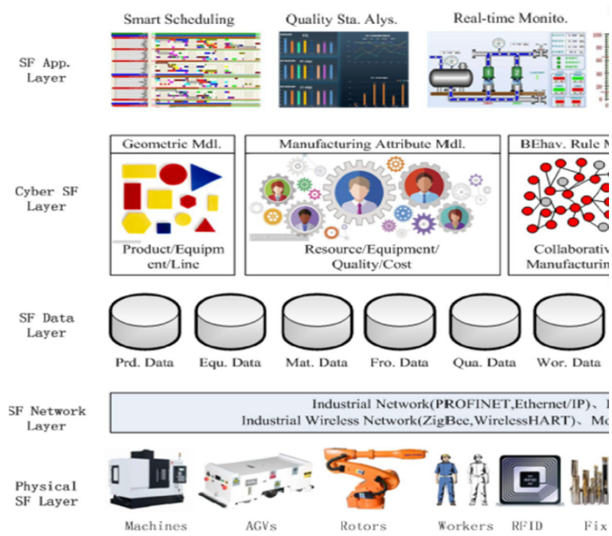

Figure 2 – Layers of a Digital Twin Architecture according to Zhang *et al.* (2019)

All these architectures are common in a layered structure and the essence of core layers, also in having an IoT infrastructure, a multi-directional data flow, high fidelity, real-time representation, and visual capabilities, here exemplified in figure 2 from the work of Zhang *et al.* (2019). These commonalities are comprehended as the dimensions or architectural requirements of any DT in manufacturing system that may be adopted when shaping the DT of a piece of its production real world. Thus, the SGRE production DT design model stands on the same principles and framework extracted from these commonalities. Such a design in SGRE is still under development, especially at IT infrastructure side (e.g., on cybersecurity and documentation domains), yet a reasonably functional design is pre-assumed in this study to define the customized specification of such DT model simultaneously with its partial deployment (in a pilot format). The focus of this paper, thus, is the technical and practical challenges during such a deployment.

A comparison in how diverse features are tackled by each of these four authors is discussed in Table 1.

	Alt. Arch. → Feature ↓	Alt. Arch. 1 (Qi *et al.*, 2021)	Alt. Arch. 2 (Yi *et al.* 2021)	Alt. Arch. 3 (Redelinghuys *et al.* 2020)	Alt. Arch. 4 (Zhang *et al.*, 2019)
1	Cloud-based	No	No	Yes	No
2	Complexity	Simple	Complex	Medium	Medium
3	Concrete description	Basic	Advanced	Medium	Medium
4	Data format compatibility	Yes	Yes	Yes	Yes
5	Diagnostic system	Yes	Yes	Yes	Yes
6	Fidelity	Yes	Yes	Yes	Yes
7	Focus on physical space	3 levels	3 objects	2 layers	1 layer
8	Focus on virtual space	4 models	2 sub-systems	1 layer	5 models
9	Focus on data flow	1 layer	1 layer and 1 sub-layer	2 layers	1 layer
10	Focus on connections	1 connection across layers	2 communication modules	2 layers: OPC UA and IoT gateways	1 network layer
11	Multi-source data compatibility (OPC UA)	No	Yes	Yes	No
12	Multi-directional data flow	Yes	Yes	Yes	Yes
13	Optimization analytics	Yes	Yes	Yes	Yes
14	Predictive analytics	Yes	Yes	Yes	Yes
15	Real time representation	Yes	Yes	Yes	Yes
16	Security	Average	High	High	Average
17	Smart decision making	Yes	Yes	Yes	Yes
18	Visualization capabilities	Yes	Yes	Yes	Yes

Table 1 – 18 Digital Twin Features in Manufacturing Analysed in Four Schemes from the Literature

OFFSHORE WIND TURBINE MANUFACTURING – MAIN ASPECTS FOR PRODUCTION DIGITAL TWIN

Siemens Gamesa Renewable Energy's (SGRE's) direct-drive offshore wind turbine comprises 3 main modules, integral blades (fiberglass), nacelle (metal parts), and tower (welded bent metal sheets), in which nacelle includes hub (interfacing blades), generator, and backend (sitting over the tower), figure 3. At time of this writing, SGRE's blade factories and nacelle factories are organizationally split, due to different material, manufacturing technologies and factory setup, while tower manufacturing is completely outsourced. Focus of this writing is limited to nacelle, and the pilot project, as a proof of concept, is defined in generator production line of D8 model, located in Brande, Denmark.

Like in any electrical motor, the generator consists of a stator that includes coils, sitting inside a rotor that holds magnets. The output of the turbine is very much depended on the gap between the coils and the magnets. Generator from one side interfaces hub by connection of the main bearing, and from the other side, interfaces backend by connection of the brake disc, figure 3.

Outsourcing nearly all the parts, SGRE OWT's generator production comprises majorly assembly processes supported by functions such as process engineering (or industrial engineering), planning, procurement, supply chain management, inventory control and warehouse, maintenance and calibration, logistics, quality control (QC), quality assurance (QA), SHE (safety, health and environment), project management office (PMO), and some more. Manufacturing technologies being used in assembly processes can simply be reduced to *moving* (by trucks, lift-trucks, cranes and movers), *placing* (precise placement and accurate adjustment of parts during mounting), and *tightening* parts (critical bolted joints), for which various digitalized, robotized, and automized solutions have been employed during time to handle big-size components (e.g., 7 meters diameter for generator rotor-house and 140 tones weight for a generator unit) and the long cycle time (175 hours for a generator unit).

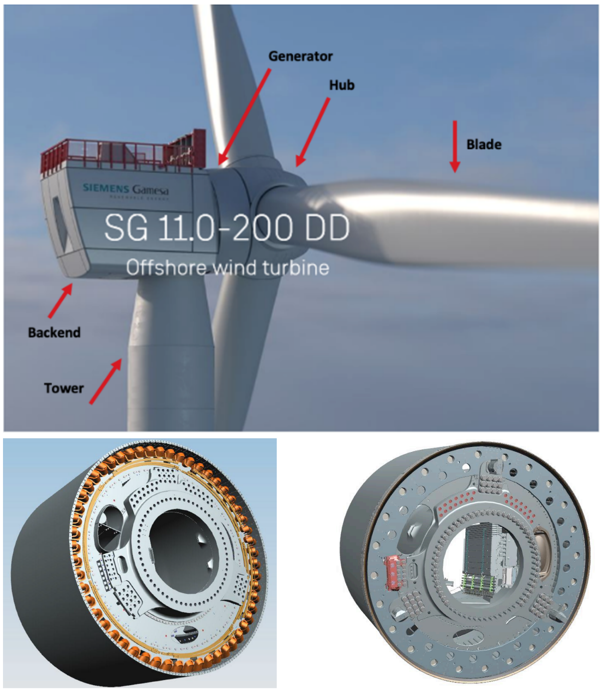

Figure 3 - OWT's Main Modules (above) and Generator Main Structure (below)

However, the main complication of the process is rooted in the fast pace of changes in design, configuration, and main parameters of both product and processes that lead to frequent changes in manufacturing setup, where the functioning sub-systems are not properly interconnected to respond to such changes synergically and agilely. Most complicated examples are when a new design releases or takt time (rate of production to meet customer demand) changes, where parameters such as sequence of operations, number of operators at each workstation, routing (material flow), procedures, tooling, and even layout might be affected and documents such as risk assessment, work-instructions, checklists, and many more might need to be modified accordingly. With high frequency of such changes, the need for a responsive system is highlighted. Following the high-level agility structure in figure 1, figure 4 is developed to show the detailed design of such responsive system in SGRE, wherein the DT's architectural requirements, extracted from state-of-the-art architectures' commonalities (feature from Table 1), are contemplated for reuse of SGRE smart assembly's DT.

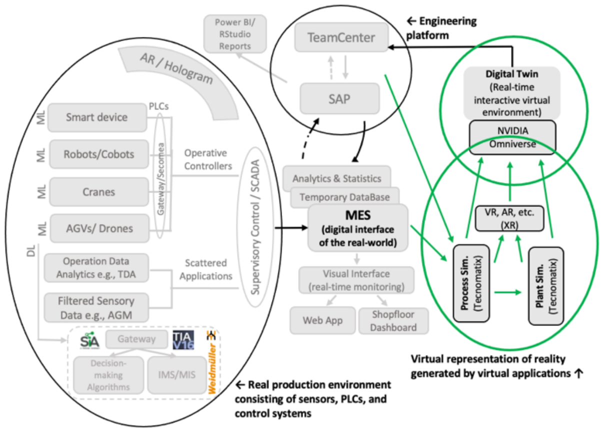

Figure 4 - Detailed Architecture for SGRE Responsive/Agile Setup with use of Digital Twin

The physical and actual space of the manufacturing system, represented in the left side of the scheme from figure 4, is perceived as production environment or factory, comprising all the tangible objects, machineries (including smart devices, robots, cobots, AGVs, XR hardware, etc.), sensors and controllers (including PLCs, supervisory controllers, etc.), systems and solutions (including OPC UA infrastructure, ML-specific controllers and servers, MES haardware, etc.), operators, tools and facilities, and all that includes the tangible effect of production support functions. Production support functions usually refers to functions that don't have direct role in adding value to the product but are required to support the process of production. Some of the SGRE's production support functions are already mentioned earlier in this chapter. The left side in figure 4 is lowlighted since the content of the real production environment is not a focus for this paper and DT models take the corresponding real-time sensory data through MES as the dgital interface of the manufacturing system.

The top side in figure 4 represents engineering platforms that includes PLM system and execution system. PLM software system, that in SGRE is Teamcenter (Levišauskaitė *et al.,* 2017), accommodates product development and generic process development, wherein engineering design process (EDP), generic product definition (GPD), and generic manufacturing definition (GMD) are conducted by process engineers. (EDP refers to design of parts and components that is conducted by individual designers. GPD refers to design of a complete product or module that is conducted by product owners or chief engineers who have insight about the whole product/module's configuration and the interfaces of the parts. GMD refers to manufacturing processes and operations whereby the allocation of material to each operation is specified.) Teamcenter is a cloud-based collaborative engineering platform that integrates all the data, information, documents, and change management history during product and process development. SAP is an execusion platform in full alignment with Teamcenter and MES mostly used for plant-specific setup and plant-based management. The top side in figure 4 is lowlighted since the content of the endgineering environment is not a focus for this paper. DT models take the corresponding planned data through build-in connectors between Teamcenter and Tecnomatix simulation software.

In the center of the figure 4, a smart MES is an inevitable element for agility design, serves the production's DT as a real-time monitoring system feeding the simulation models by actual (i.e., real-time) data and comparative analytics. MES is a central platform acting as an interface for automation of functions which are serving the production either by adding direct value or by supporting it. MES in SGRE acts first as a help for operators by providing them with digital guideline and all the required information and documents they may need before, during, and after an operation. It also facilitates the communication that an operator may need to make with any of the support functions during an operation. MES automates the collection, storage and analysis of data, making most of the main parameters of the production process measurable and controllable. All the collected actual data from an operation are stored, displayed in live monitoring format (convertible to reports integrated with Power BI applications), processed as comparative analytics compared to engineering data from PLM system, and run down through a time-series database to feed the simulation applications. In figure 4, MES, its content and setup is not a focus for this paper while its connection to DT models, specifically to virtual systems such as simulation and XR systems, is a part of the pilot implementation whereby the corresponding technical and practical challenges are discussed thoroughly.

The right side of the figure 4 represents virtual applications in use, each one having different role in fulfilling responsiveness/agility of the overall system. Even applications such as AR, with utilization in shopfloor (i.e., actual space), are sitting on the right side of the figure based on their virtual nature and needed infrastructure. VR, NVIDIA Omniverse, and all simulations including plant simulation and process simulation sit also on this side. SGRE uses Tecnomatix as the simulation software.

NVIDIA Omniverse (https://nvidia.com) is a platform (even if not the only one in the market) for integration and collaboration of 3D-graphics visual applications. Using its own brand GPU (graphics processing unit) that is customized for game industry, NVIDIA Omniverse has capability of graphics optimization, parallel computing, and life-like graphical animated visualization. On such an environment, not only different applications in virtual space are integrated and synchronized in a life-like animated format with real-time interactive visual interface, but also simultaneous collaboration of engineers working on different applications enables a real-time concurrent engineering in 3D environment. In figure 4, NVIDIA Omniverse system closes the feedback loop of the entire system through direct connection to

PLM system where the engineering change management is systematically organized. Such a closure enables full agility where the engineering change management system, as a part of the PLM system, by support of the DT, acts faster and more effective during a change. In other words, in an agile loop, any change or perturbation with origin in actual physical production environment is reflected on DT, analyzed, verified and with alternative solutions is sent back to the engineering environment (i.e., the PLM system) for adoption and adaption. NVIDIA Omniverse is recognized as the DT platform in SGRE manufacturing system, integrating various virtual world's systems backed by real-time data. Without such an integration, it is impossible to imagine a twin of a process like production/assembly process, with numerous human, tools and machineries equipped by sensors and PLCs, feeding various virtual systems. Figure 5 is a comparative picture showing simulated model vs. life-like animated graphics by NVIDIA Omniverse.

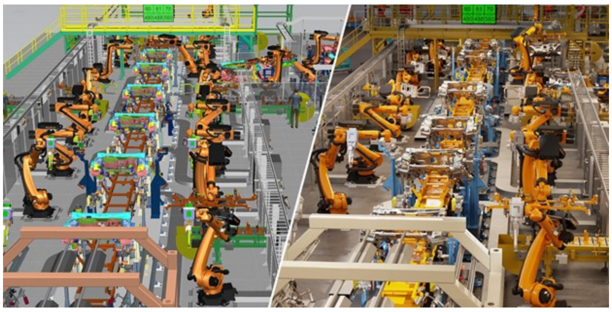

Figure 5 - Simulated Model by Tecnomatix Process Simulation (left) and Life-like Animated Graphics by NVIDIA Omniverse with Data from Tecnomatix as Input (right) – https://nvidianews.nvidia.com

Studies, in production/assembly's DT, or generally in industrial DT, have rarely discussed the final format of such a DT's output and its interface. Most of studies remained at the level of system design and architecture, without presenting a case-customized configuration and final format for it. Therefore, in reply to *how a real-time assembly DT looks like*, a knowledge-based answer may point out the architectural state of the art, and a careless answer may refer to some animated simulation commercials. However, it is commonly perceived that the final DT should have a visual interface, by common sense exhibitable on a display in graphical life-like format. 3D simulations and industrial animation software are gradually moving in that direction to make integrated life-like graphical expression of the real world, however, there are still a lot of challenges for industrial hardware to handle the heavy graphics of such a detailed DT. Yet, the SGRE production DT itself is placed at virtual space of the manufacturing system due to its nature and the final output format.

With focuse on the right side of figure 4, this paper highlights technical and practical challenges in implementation of a DT pilot. The green border in figure 4 shows the area in which these challenges are seen.

CHALLENGES OF DIGITAL TWIN IN SGRE OFFSHORE WIND TURBINE PRODUCTION

The architecture of a smart production DT is enabled by development of the recent technologies, however, in practice of getting to a functional DT that generates operational value, manufacturing industry struggles still to overcome some technical, contextual, and economical challenges.

Figure 6 - Application of VR Glasses and AR Holo-lenses in SGRE System Engineering Lab.

Among technical challenges, the most part is rooted in incompatibility of the applications when it comes to their interconnectivity and integration. Various AR and VR software and hardware brand in the market, with several features and different levels of industrialization, security, and compatibility, require an extensive assessment and risk analysis to be selected for the purpose, that in large scale, demands a broad requirement management, leading to a broad stakeholder management. Since most of these applications are already in use almost as *randomly* by scattered teams and departments for different purposes (e.g., work instruction, training, ergonomics, etc.), integration and reuse of what we have in house also require a solid knowledge sharing process ending up into a proper documentation, that is lacking. Lack of knowledge for development of some desired or SGRE-specific features for any of the virtual applications is also a risk, however not a showstopper.There are cons. and pros. in either developing the knowledge in house or just investigating in the market for buying third party connectors, API packages or developers' service solutions. Figure 6 shows the VR glasses and AR holo-lenses that we use in our system engineering lab.

Heavy graphics, both in running simulated models, that is the main environment for VR and AR holo-lenses applications, and in any interactive virtual software, is another challenge, with effect of a very slow functionality of the applications and lagging movements in the environment. NVIDIA Omniverse is selected as a DT-integration platform to also address the heavy merged graphics problem by use of its own-brand GPUs which are developed to stay competitive in interactive gaming market. In its main license package, NVIDIA Omniverse has more than 42 connectors and plug-ins and its compatible with more than 40 file formats in import and export. However, the API and connector to

Tecnomatix software is still under development and currently provided by a third party called Netallied Systems. NVIDIA Omniverse is not an SGRE's business application yet. That is, the trial license needs a business-case and an IT demand seeking for IT approval. From cyber security point of view, until a software becomes an SGRE's business application, sitting on its clouds and fully integrated in its infrastructure, it's not secure. That means the business data and documents can not be uploaded, saved or shared on the software.

Among Tecnomatix simulation software modules, Plant Simulation and Process Simulation are contributing to the SGRE responsiveness and smart assembly DT. Based on the strategy of the developer company, Tecnomatix simulation modules are not interconnected, whereby challenges are caused when a change is occurred in a process while the effect is not seen in the simulation of the overall plant (i.e., production line). As mentioned before, heavy graphics for this software is also a problem, especially for its real-time data rundown. NVIDIA Omniverse as an alternative graphical solution is already discussed. Limited compatibility with interface systems, specially with various brands of VR and AR software/hardware in the market, limits the choices to a few brands, that increases the risk for development of features in long term. HTC-Vive is the only compatible VR software with Tecnomatix, and Netallied is the only connector in the market between Tecnomatix and NVIDIA Omniverse. Although, there are some bridge software, such as Morw3D, that can come in between Technomatix and HTC-Vive to increase the compatibity and release more potential of features through its APIs and connectors.

Among practical challenges during simulation, creation of a customized library and 3D graphics is the highlight. However, it's not easy either to generate a process-based logic of the production flow for the simulation design and to make codes for automizing a template for the design so it can update the whole model upon change of one or more parameters. Figure 7 shows the process-based logic of the SGRE's D8 generator production flow, simulated model of the same production line (in offline mode), and the view through VR glasses in the same simulated production environment, where the standpoint is the top right gate through which the truck leaves the factory.

On actual space side, in implementation of technologies such as ML and OPC UA, availability of data (i.e., if the data, by any means, is collected and properly stored), accessibility of data (through suppliers, PLCs, or based on a relevant permission), and quality of data (i.e., being meaningful in terms of relevancy, completeness, accuracy, timeliness, consistency, validity, and uniqueness) are the main technical challenges. Also, IT approval for trial and use of infrastructure, in addition to provision of temporary cyber security until a company-wide integration, especially in OPC UA project, are the contextual challenges that SGRE is struggling with. Almost similar challenges are on the way for Time Series database (TSDB) implementation in addition to the IT approval for a temporary server as well as permission for trial connection to the live business applications. The latter has become a showstopper until the new amendment in the local protocols and procedures is created and approved. These kinds of challenges are common in APIs and connection development too, however in this case, the entire knowledge, cyber security standards, and documentation is under development from scratch.

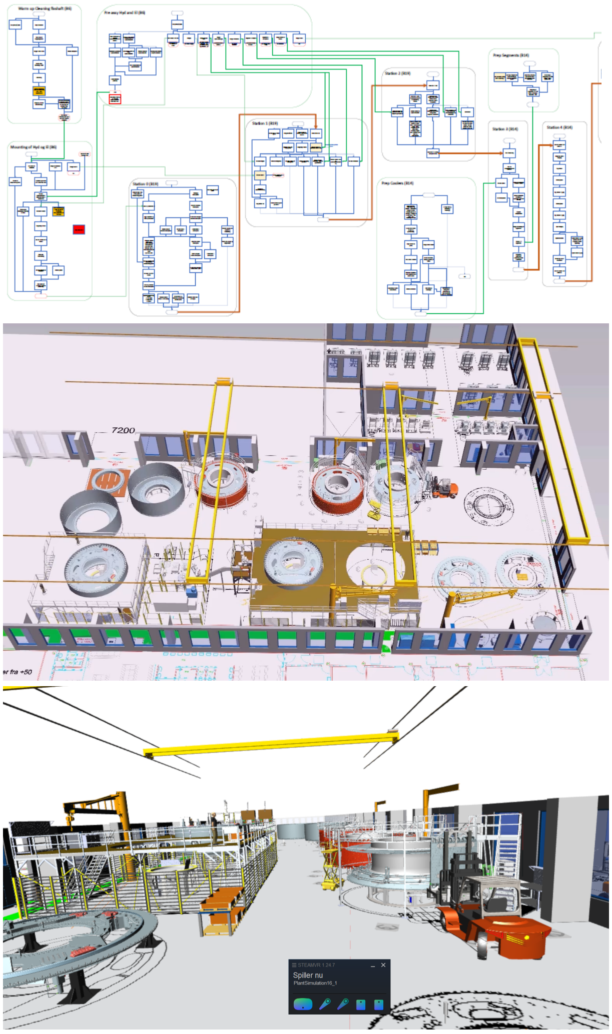

Figure 7 - From top: Process-based Logic of the Production Flow, Simulated Model of SGRE's D8 Generator Production Line, and the View seen through VR Glasses.

In actual space of the DT, where individual digitalized, robotized, or automized solutions such as cobots, as well as MES, are implemented, the compatibility of the software with interfacing assets and systems is a hurdle. However, some socio-technical challenges such as human interaction and adoption by operators in shopfloor, also compliance to the data privacy and general data protection regulation (GDPR) standards are bigger challenges. The latter also applies for 3D collaborative environment in DT where operators, as a type of system elements, should use wearable sensors to reflect their moves and ergonomics while working. However, the

European GDPR's protocol doesn't permit to identify and trace an operator by all detailed movements, due to the risk of misuse of data for other purposes such as incentive systems. Therefore, using sensor activation programming, or PLCs, to activate sensors only in a certain physical area where the operator conducts actual work (i.e., operation), is under investigation. In addition to all, contextual challenges such as long lead time and complication of permission for a trial connection to the live business applications, or a test area, and IT approval for software trial and use of infrastructure are also bumps on the way of implementation of such concepts.

Economically, investment on these technologies in the format of budget allocation to their implementation in an optimum scope is under discussion. Provision of hardware and software (where applicable) and project resources are not the only cost to consider. In some cases where individual digitalized, robotized, or automized solutions are implemented, or for implementation of ML and OPC UA, some of the assets should be upgraded, or completely refurbished, to a PLC compatible asset. Such process for most of these assets are too expensive, either due to complication (e.g., adjustment tools for placement of the stator in rotor-house) or due to the number of the assets (e.g., more than 50 electrical and manual torque wrenches).

During the implementation of such a smart assembly DT, there is always an ongoing economic-strategic discussion whether the related knowledge should be developed in-house through trainings and employment of specialists, so to own the knowledge and the specialists for any further expansions, or such knowledge is better to be bought from external parties, much faster and more efficient with necessary support.

Due to the multidisciplinary nature of DT implementation, there are a lot of overlaps between responsibilities and projects of various departments and teams working as system engineering, digitalization, smart manufacturing (or industry 4.0), operational excellence, technical excellence, smart tooling, NPI process engineers, and even IT solution architects. No doubt a functional DT is not made without an organized collaboration between all these departments and teams using the lump sum of all their competencies and expertise. However, lack of a common understanding of the new smart technologies including DT, and their dimensions, potentials and extent, have caused some challenges in defining the ownership of the implementation project, thus in taking the practical steps. The challenges here described are structured in categories presented as a Table in the appendix.

More detailed description of *each application*, as a stand-alone solution in manufacturing context, and the challenges in its implementation, can be a separate discussion with focus on the areas involved in that discussion (e.g., the application's connection to the interfacing systems). But in this paper, the vision of the study is to keep up the big picture of *why these challenges are taken in the context of DT creation, with involvement of various applications, all serving system's responsiveness,/agility in an integrated format*. So, the discussion here remains limites to the introduction of such challenges, their categorization and classification (the table in appendix), as well as the suggestion of some alternative solutions that SGRE has investigated.

DISCUSSION AND FUTURE WORK

Based on the described challenges, for the implementation of a pilot scope of smart assembly DT, first the ownership of the project and the framework of the collaboration between teams, should clearly be defined, so the direction of budget allocation, IT requests, and technical resources is determined. The first practical step, however, is to start with requirements extracted from the design's common features. To fulfill such requirements, the configuration is proposed, and the alternative technologies and brands are assessed. The strategy was to reuse as many existing systems (software and hardware) in SGRE as possible. A solid business case supported by a decision matrix, showing why a technology or brand/vendor is selected in the configuration, could help remarkably both for budget and resource allocation and for the foundation of the relevant IT approval request.

Scoping implementation of each technology/system, as a component or subsystem of the intended DT, in a work-package or project format, helped a lot not only to assign relevant resources, but also to breakdown the structure into practical steps providing a better overview for the budget owners where and why they are spending money. Since each single work-package could, as an individual solution, add value to a part of manufacturing system in a large-scale implementation, an effort to sell them individually to internal customers, helped with cultivating the culture of using that technology before the final DT is picturized. For example, simulation of the layout and processes of the production, in offline mode (not running with actual real-time data), can help with optimization and balancing of the material flow, and design of new spaces (or utilization change of a currently in use space). Individual digitalized, robotized, or automized solutions such as cobots help also to optimize specific process or remove operational and ergonomic risks. VR and AR also, before connections to serve DT concept, are being used in training operators and accessing work instruction content in operative occasions (as it's being used in offshore installation and execution team). Although, when the value of an individual work-package is proven and the experts are identified, it's not easy to convince the internal customers that the higher objective is the connection of all these solutions and an actual DT, since they tend to buy more of the solution and services which is bringing an immediate instant value rather than waiting for a bigger solution to fulfil a business objective later.

The effort to implement a proof of concept of a functional DT of SGRE smart assembly is still ongoing. However, the practical scope is not a mystery anymore. Only through such implementation, the integration loop (figure 1) is closed and verification of agility design becomes possible. Therefore, the future work is reasonably the completion of such implementation before defining the agility pilot scope, whereby the SGRE-specific DT design and its significant role in responsiveness of the system will be validated.

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APPENDIX - SUMMARY OF CHALLENGES FOR DIGITAL TWIN IN MANUFACTURING.

Challenge category → Top technologies in SGRE production DT scope ↓	Technical	Contexual	Socio-technical	Economical
Digitalized, robotized, or automized individual operation	Compatibility of the software with different tooling brand	Strategic overlap across teams and functions Permission for trial connection to the live business applications Documentation of the new system IT approval for software trial and use of infrastructure	Adoption by operators in shopfloor Privacy and GDPR compliance	Upgrade/ refurbish assests by PLC compatibility Budget for hardware Budget for software
OPC UA / Machine connectivity	Data availability (generated and properly stored) Data quality (meaningful data by relevancy, completeness, accuracy, timeliness, consistency, validity, and uniqueness)	Data accessibility (through suppliers, PLCs, relevant permissions) Cyber cecurity Documentation of the new system IT approval for trial and use of infrastructure	—	Upgrade/ refurbish assests by PLC compatibility
ML	Data availability (generated and properly stored) Data quality (meaningful data by relevancy, completeness, accuracy, timeliness, consistency, validity, and uniqueness)	Data accessibility (through suppliers, PLCs, relevant permissions) Documentation of the new system IT approval for trial and use of infrastructure	—	Upgrade/ refurbish assests by PLC compatibility
MES	Compatibility of software (application-based) with interface systems as per Fig. 5.	Strategic overlap across teams and functions Permission for trial connection to the live business applications Documentation of the new system IT approval for software trial and use of infrastructure	Adoption by operators in shopfloor Privacy and GDPR compliance	Budget for hardware Budget for software
Plant simulation	Heavy graphics Automization of template for change accomodation Creation of customized library and 3D graphics Compatibility with interface systems as per Fig. 5. Interconnectivity across simulation modules	Process information, dependencies, requirements and specifications Documentation of the new system	—	Budget for software
Process simulation	Heavy graphics Automization of template for change accomodation Creation of customized library and 3D graphics Compatibility with interface systems as per Fig. 5. Interconnectivity across simulation modules	Process information, dependencies, requirements and specifications Documentation of the new system IT approval for software trial	—	Budget for software Business case for each module (modular license)
VR	Heavy graphics Compatibility with interface systems as per Fig. 5. Industrial features and applications	Cyber cecurity Knowledge: development in-house or third party purchase Documentation of the new system IT approval for software trial and use of infrastructure	—	Budget for hardware Budget for software
AR	Heavy graphics Compatibility with interface systems as per Fig. 5. Industrial features and applications	Cyber cecurity Knowledge: development in-house or third party purchase Documentation of the new system IT approval for software trial and use of infrastructure	Adoption by operators in shopfloor Privacy and GDPR compliance	Budget for hardware Budget for software
Time-series DB	Data availability (generated and properly stored) Data quality (meaningful data by relevancy, completeness, accuracy, timeliness, consistency, validity, and uniqueness)	Permission for trial connection to the live business applications Data accessibility (through suppliers, PLCs, relevant permissions) Cyber cecurity Documentation of the new system IT approval for temporary server	—	—
3D Collaborative platform	Compatibility with interface systems as per Fig. 5. Industrial features and applications Interconnectivity with other virtual applications	Cyber cecurity Knowledge: development in-house or third party purchase Documentation of the new system IT approval for software trial	Privacy and GDPR compliance	Budget for hardware Budget for software
APIs	Knowledge under development	Permission for trial connection to the live business applications Cyber cecurity Knowledge: development in-house or third party purchase Documentation of the new system IT approval for temporary server	—	—
Cobots	Compatibility of the software with interface systems in shopfloor	Strategic overlap across teams and functions Documentation of the new system	Adoption by operators in shopfloor	Budget for hardware