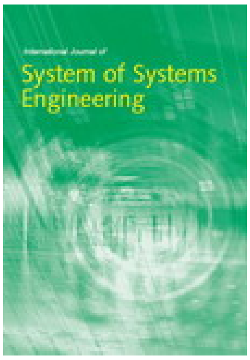

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Mehrnoosh Nickpasand, Henrique M. Gaspar

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Agile design framework for offshore wind turbine manufacturing

Mehrnoosh Nickpasand*

Department of Ocean Operations and Civil Engineering,
Norwegian University of Science and Technology,
Ålesund, Norway

and

Department of Operational Excellence,
Siemens Gamesa Renewable Energy,
Brande, Denmark
Email: mehrnoosh.nickpasand@siemens-energy.com
*Corresponding author

Henrique M. Gaspar

Department of Ocean Operations and Civil Engineering,
Norwegian University of Science and Technology,
Norway
Email: henrique.gaspar@ntnu.no

Abstract: This study proposes an agile design framework for the offshore wind turbine (OWT) manufacturing system of Siemens Gamesa Renewable Energy (SGRE). The manufacturing process involves complex interactions among subsystems, requiring responsive adaptation to changing market demand and technological advancement. Traditional proactive change management strategies being inadequate, a reactive strategy using system engineering principles enhances agility. The framework integrates System of Systems Engineering (SoSE) methodologies to create an architecture supporting digital tool interoperability and subsystem communication. Key components include a manufacturing execution system (MES) and digital twin (DT), which use artificial intelligence (AI) deep learning (DL) models for real-time analysis and decision-making. The framework employs iterative methodology involving technology assessment and risk analysis to construct an agility portfolio for modern manufacturing. The findings aim to enable swift response to changes while maintaining operational excellence.

Keywords: agility; SoSE; system of systems engineering; portfolio management; offshore wind turbine (OWT) manufacturing.

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Biographical notes: Mehrnoosh Nickpasand is a PhD Researcher at the Department of Ocean Operations and Civil Engineering, Norwegian University of Science and Technology (NTNU), and a Senior System Engineer at Siemens

Gamesa Renewable Energy (SGRE). She has been holding senior positions as Technical Project Manager, System Engineer, Process Engineer, and Advanced Manufacturing Lead Engineer in industries such as Oil & Gas, Wind, Automotive, Telecommunication, and Construction at international and world-class companies. Her academic focus is on System Design and System Architecture at System of Systems (SoS) level. https://www.linkedin.com/in/mehrnoosh-nickpasand-5995272a/

Henrique M. Gaspar is a Professor at the Department of Ocean Operations and Civil Engineering, Norwegian University of Science and Technology (NTNU), with works in the field of design, modelling, simulation, and digitalisation of maritime systems. He has a PhD in Marine Engineering from NTNU, with research collaborations at UCL (UK) and MIT (USA). Previous professional experience as Senior Consultant at Det Norske Veritas (Norway) and in Oil & Gas in Brazil. https://www.ntnu.edu/employees/henrique.gaspar

1 Nonresponsive OWT manufacturing system; status quo and research motivation

Offshore wind turbine (OWT) manufacturing flow is a result of interactions between many functions and dependent subsystems. Changes in main parameters can impact dependent functions, with effects continuing, in a domino pattern, throughout the value-adding processes. Complexity increases when rapid changes in design, configuration, technology, and market demand impact the value chain and trigger frequent multidimensional changes in manufacturing setup requiring quick and proper responses.

Siemens Gamesa Renewable Energy (SGRE) pursuing smart factory development through industry 4.0 and IoT, has adopted numerous smart solutions through automation, digitalisation, and robotisation of manufacturing functions. However, these solutions exist in fragmented and detached formats, focusing on specific areas' operational excellence. The lack of interoperability in an integrated architecture makes them complexity factors during changes. Despite reliance of all these solutions on data-driven tools for system behaviour dynamic analysis, effective system wide information transmission at the right time and in the right pattern, as an effective and quick response, remains a challenge.

The well-established change management system is one of these systems which operates separately from other solutions, based on proactive identification of changes and long manual risk assessment. For example, when a new tact time (i.e., rate of production) is required to meet the market demand, parameters like operation sequences, operator numbers at each workstation, material flow (routing), procedures, even layout might be affected and documents such as risk-assessment, work-instructions, and checklists may need modification accordingly. This process relies currently on domain experts' knowledge, where production engineers and leads try out different scenarios with parameters to determine optimal setup. The final configuration then directs impacted areas to plan changes and initiate *change request* in the change management system.

With frequent complex changes, a responsive system is essential. The time constraints do not allow existing proactive strategies to identify every if-then scenario and plan for it. A reactive response strategy, backed by a reliable architecture and risk assessment is needed to promote interoperability, comprehensibility, learnability, and scalability of the system for effective response to unpredictable changes in uncertain times. System engineering principles provide a foundation for these objectives.

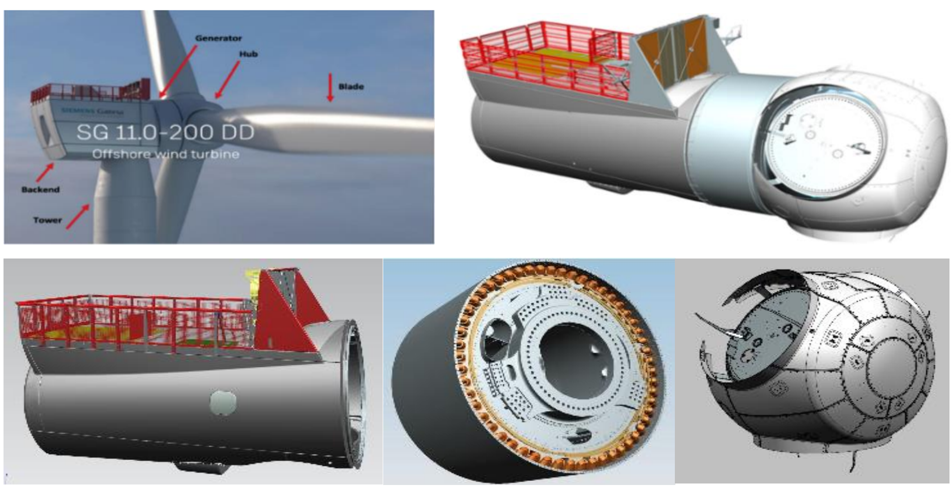
In absence of a strategy and comprehensive framework for technology selection and purposeful system integration toward agility as high responsiveness, this paper aims to fill this gap by defining a holistic strategy that includes architecture design, interfacing concepts portfolio construction, and pilot implementation and validation.

2 SGRE OWT product and process; context and boundaries

2.1 SGRE OWT product

SGRE direct-drive OWT comprises three main modules: integral blades (fibreglass), nacelle (metal parts), and tower (welded bent metal sheets), Figure 1, top left. The nacelle, Figure 1, top right, includes backend (sitting over tower), Figure 1, bottom left, generator, Figure 1, bottom middle, and hub (interfacing blades), Figure 1, bottom right. SGRE blade and nacelle factories operate in split format due to different materials, manufacturing technologies, and factory setup, while tower manufacturing is outsourced. Production data for proof of concept (PoC) in this research comes from nacelle assembly lines in Brande, Denmark, and Cuxhaven, Germany.

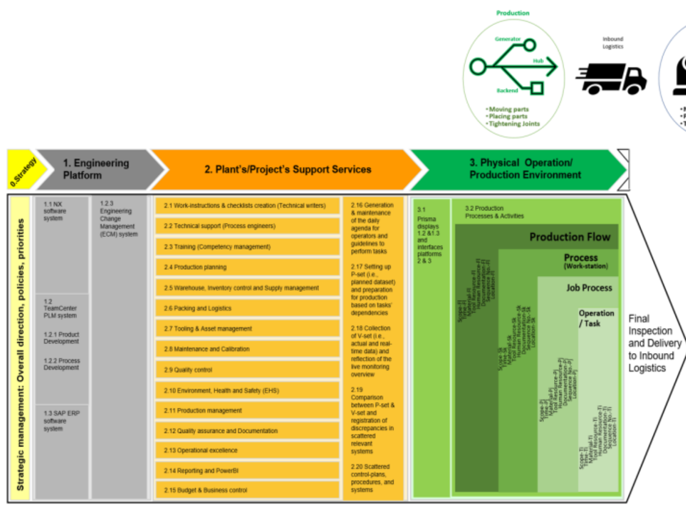
Figure 1 SGRE OWT main modules (top), nacelle (middle), backend (bottom left), generator (bottom middle), and hub (bottom right) (see online version for colours)



2.2 SGRE OWT nacelle production flow and manufacturing process

SGRE OWT Nacelle manufacturing comprises three main phases: production, pre-assembly, and offshore installation or execution, Figure 2, top. In some SGRE plants, production and pre-assembly are merged (e.g., Cuxhaven in Germany), while in others, like Brande factory in Denmark, it's located far from the pre-assembly yard in Esbjerg harbour. Inbound logistics manage material flow within SGRE facilities and suppliers, while outbound logistics deliver products to wind farm sites. The construction process mainly involves assembly, simplified into three operations: moving parts (transportation by trucks and cranes), placing parts (precise positioning and adjustments during assembly), and tightening parts (fastening bolted joints). Various manual, automated, and robotised solutions manage these operations' complexity caused by large components (up to 15 m long, weighing over 410 tonnes) and long cycle time (exceeding 200 h for generator unit production).

Figure 2 SGRE OWT nacelle manufacturing process from production to execution (top) and the manufacturing system behind the production of OWT (bottom) (see online version for colours)



The manufacturing system in each phase is semi-identical, comprising same elements and principles, while following identical infrastructural protocols, but differs in content. It means the methodologies proposed in this paper for developing Agility in SGRE OWT manufacturing apply to all phases, despite varying environmental factors. The case study uses data from the OWT nacelle module production.

Outsourcing nearly manufacturing of all the parts, SGRE OWT nacelle production lines (Figure 2, left) primarily involve assembly processes, including value-adding and required non-value-adding physical activities. These activities are performed by production and construction teams and operators using hardware (tools, machinery, displays) and software UIs in factories across SGRE plants. Each factory may have multiple production halls containing entire or partial production lines. Production line refers to the assembly of an OWT module through sequential mechanical and manual operations at workstations. SGRE OWT nacelle production lines are continuous flow assembly lines that mass produce standard products, where material moves through workstations in pre-defined sequence at a steady rate (tact time). The production cycle includes a main assembly line and pre-assembly stations for preparation activities like unpacking, cleaning, cable termination, and side-part assembly.

The manufacturing system behind OWT production comprises four main platforms (Figure 2, bottom). Following the platform numbering, the process begins with *strategy* (platform 0), which defines the overall direction and priorities. The outcome, in the format of strategic priorities (e.g., guidelines on cost-out, delivery time, quality, or product promotion), compliance protocols (e.g., market agreements, political agreements, national and international directives, or environmental commitments), financial strategies (e.g., currency management policies or procurement directions), product strategies (e.g., portfolio decisions, product range policies, or market trend guidelines), sales strategies (e.g., competition and collaboration strategies or customer management requirements), and IT infrastructure strategies, serves as input for the *engineering platform.*

Engineering platform (platform 1 in grey, Figure 2, bottom) handles product and process development. Product specifications are defined through Siemens NX design software and Teamcenter PLM (product lifecycle management) system. From PLM system, the generic process specifications are taken over by SAP ERP system, compiled into manufacturing parameters (e.g., routing, material flow, tact-time, BoM, worker allocation), and customised for each plant, forming the manufacturing framework and plant-specific production setup. The platform's outcome is the intended content of the production flow and manufacturing parameters, called planned dataset (P-set) or to-be dataset.

Support services, platform 2 in orange (Figure 2, bottom), compiles manufacturing parameters and its intended content into practical parameters for production practice. Support services define and manage the framework and practicalities of the manufacturing setup to achieve P-set. Most functions in this platform are currently performed manually or semi-digitally through scattered software systems.

Operation/Production environment, platform 3 in green (Figure 2, bottom), contains actual processes and activities (function 3.2) which add value to the raw material using tools and machinery, hardware and software, sensors and controllers, servers and databases, and human resources. Function 3.1 is the current execution software system (Prisma) that interfaces support services and production platform, displaying P-set from engineering platform.

In production environment, physical activities are identified by content and dependencies. Competent operators use assigned tools to apply procedures (described in documents or embedded in coded algorithms) on determined materials at specific locations in pre-defined durations. These eight parameters define an operation, while operations (i.e., tasks) form job process, job processes form workstation processes, and workstation processes establish production flow. These parameters are measurable, and their value are initially defined by engineering platform. Their importance stems from their direct impact on manufacturing performance, derived from production practice and outcome, where changes in their values may trigger system response through agility.

The production flow breakdown (function 3.2, Figure 2, bottom) from SGRE manufacturing system taxonomy shows hierarchical process layers, each defined by eight variables: scope (process description) time (duration), material (to assemble or consume), tools (hardware/software), human (operators assigned to the job), documentation (paper-based or digital information to use or register), sequence number (activities order), and location (in agreed coordination). The index i counts tasks (Ts), j counts job processes (Ps), k counts workstations (Ss), and l counts production flows (Fs) in the factory.

These parameters, along with spatial and environmental parameters, define the production simulation and its detail level. These parameters, along with spatial and environmental parameters, define the production simulation and its detail level. Correlation between variables at each layer describes its activity behaviour, while how activities bundle at each layer to define the upper layer explains why changes in values of some variables lead to more important changes at upper layers. These correlations are studied at interface analysis, where parameter deviations are tracked through real-time data.

During production practice, real-time values (e.g., actual production rates, quality metrics, machinery status, operations durations, tools locations, and operator numbers) are generated for the eight manufacturing parameters as V-set or as-is dataset, while they may differ from intended values (P-set). If so, system performance is affected, and outcome may not stay within expected ranges defined by the engineering platform. Such discrepancy between P-set and V-set is currently handled manually by production managers and leaders. The current setup visibly struggles to meet modern manufacturing key performance indicators (KPIs) focusing on business competitive advantages like responsiveness, flexibility, quality, and efficiency (Banáš and Chovanová, 2023).

Benchmarking the current SGRE OWT manufacturing system model, Figure 2 against modern agile manufacturing systems like Turner and Oyekan (2023) and Kumar et al. (2020), reveals SGRE's lack of strategy for technology selection and integration in industry 4.0/5.0. Information technology's (IT) role in agility infrastructure and foundational understanding of operational metrics frame SGRE OWT manufacturing relative to emerging technologies like digital twin (DT) and artificial intelligence (AI) learning models (e.g., machine learning (ML) and deep learning (DL)), emphasising virtualisation-supported decision-making.

To enable agility in current manufacturing model, this paper proposes incorporating a portfolio of these technologies into SGRE manufacturing system architecture, prioritising them by their agility-enabling role. Each technology's pilot serves as PoC to verify system's agility improvement while indicating implementation effectiveness in other system components coordination.

3 Agility design for SGRE OWT manufacturing

3.1 Agility enablers portfolio, feasibility and PoCs

Aiming to propose a framework for agility enablers identification and development in SGRE, system of systems engineering (SoSE) principles and methods are helpful. SoSE holistic perspective, focusing on overall functionality and performance of complex systems, could propose effective frameworks for evaluating interaction across subsystems. The framework here is a portfolio of twelve technology work packages (WPs) and one extra WP, containing administration guidelines and templates to manage such portfolio, Figure 3. This framework provides decision-making insight for selecting state-of-the-art technologies as architectural elements for implementing agility in SGRE manufacturing system, Figure 2.

In this portfolio, Figure 3, left, each WP represents a technology or concept to be developed and verified as a project for a business use case before its integration into the agile manufacturing architecture. Each development project, highlighted in title by its commercial or scientific platform and in content by its summary and objectives, is scoped over a pilot implementation (PoC) and its system connections, compliant with the agility principles and integrated architecture. These WPs are either selected from market off-the-shelf technologies or reused from SGRE systems to enable and enhance manufacturing agility. The technology selection spans from digitalisation and robotisation solutions (e.g., digital tightening data analysis (DTA) and collaborative robots (C-robots)) in production environment (platform number 3 in Figure 2, bottom) to DT components and virtualisation platforms (e.g., simulation systems, extended reality (XR), and NVIDIA) which form a new platform in the architecture (virtual platform number 5 in Figure 4).

Figure 3 SGRE OWT agile manufacturing technology portfolio, left, and high-level portfolio management framework, right, where 8 deliverables in this research are highlighted (see online version for colours)

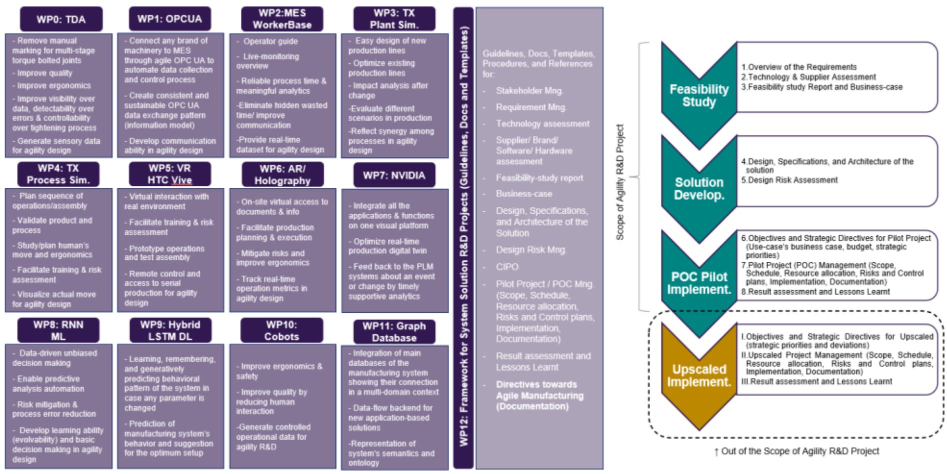
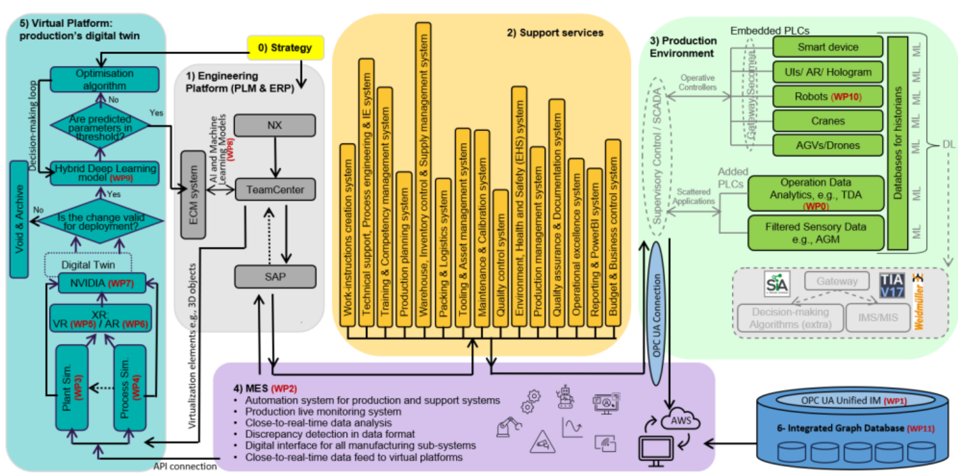


Figure 4 Agility architecture for SGRE OWT manufacturing system (see online version for colours)



To clarify the scope of each PoC development and deliverables, the high-level framework, Figure 3, right, is created based on system engineering and project management fundamentals. This framework has already been adopted by some SGRE teams dealing with innovation and development concepts. In the figure, phases in green and numbered deliverables indicate the current agility R&D project scope, while the upscaled implementation phase is not part of this research.

In the framework, Figure 3, right, each development phase represents a project with different nature and requirements. Hence, each phase demands distinct project team with distinguished knowledge, project management strategies, timeframes, budgets, and resources. For example, the feasibility study phase for a digitalisation WP requires finance and business control teams, technology specialists and domain experts, with project manager focusing on coordination and communication to collect and manage requirements through different resources and create a business case. While the solution development phase, requires various engineers (system engineers, tooling engineers, production engineers, product design engineers, cybersecurity engineers, software engineers) to design, calculate, risk assess, and define the digital system specifications.

For verification and pilot implementation, the project team must have expertise to create the use case. This may require specific experts like fibreglass specialists for mock-ups or 3D simulation experts for digital solutions. The project management strategies align with this phase's nature. In the upscaled phase, the project team becomes a multidisciplinary solution construction team including cloud experts and local plant key users, with resources different from previous phases.

System development framework in SGRE in the past years, however, has been unstructured and bottom up, where million-budget allocations were made to a concept and its upscaled implementation based on a high-level business case, with mixed project teams assigned to all phases simultaneously. Projects like Agora, Athena, and OneMES exemplify this. Due to the novelty of these systems, after a couple of years, it became clear that in-house knowledge for such development was insufficient. Typically, the way out was outsourcing the solution development, where the unforeseen cost in limited project budget and timeframe prevented a thorough supplier assessment to find niche market and specialist companies. This led to agreements with existing approved suppliers (providers of other types of services) based on discounts and trust. As a result, the project became a sandbox for the supplier (with non-relevant background and expertise) to practice and develop solutions for SGRE's needs. In practice, such an outsourcing deal provides only man-hours to experiment the development rather than development expertise, resulting in longer timelines and higher risks. The delivery times and reduced scope of these projects confirm this analysis.

3.2 Agility architecture for SGRE OWT manufacturing

Agility architecture for SGRE OWT manufacturing is synthesised as in Figure 4, combining the existing manufacturing model in Figure 2 and the conceptual solution portfolio in Figure 3 (the 12 WPs are traceable by numbers in red).

In this architecture, three platforms are added to the existing manufacturing process (Figure 2): platform number 4 in Purple, i.e., *Manufacturing execution system* (*MES*), platform number 5 in Turquoise, i.e., *Virtual platform* containing *DT*, and platform number 6 in Blue, i.e., *Graph database*.

MES (platform 4 in Figure 4) is a digital interface between manufacturing segments, bridging between engineering platform, support services, and production environment. It controls dataflow and ensures subsystem harmony while generating real-time analytics for production monitoring and detecting parameter discrepancies (Figure 2, bottom) for further validation at platform 5. As a production automation system with digital interface across platforms, MES automates *integrated analytics generation*, *perturbation registration*, and *service providers communication*. To achieve these, MES incorporates functions 2.16–2.20 from support services (Figure 2, bottom) and integrates other scattered manual or semi-digital services through one application.

As an example, it can generate daily operator agendas based on competencies and task dependencies by integrating with training management and production planning systems. This digital agenda replaces paper-based SWS (standard worksheet) with enhanced information and guidelines. The MES at this scope requires modular logic to keep agenda's flexibility upon set-point changes. PoC of this platform (*WP2*) was implemented across three SGRE Generator production workstations as a modular system with interactive UI (user interface). The project met success criteria, with methodology documented in a separate paper (under review).

In the agile SGRE setup, Figure 4, production activities in platform 3 receive input data through MES, as set-points in PLCs (programmable logic controllers) and other controllers (for automated processes) or as read-only on MES UIs (for manual processes). Smart devices with displays like watches (*WP2*), tablets, mobiles, and PCs, or holography devices like hololenses, holoscreens, and AR (augmented reality) glasses, can serve as UI for application-based MES. Other hardware, equipment, and facilities, including smart ones with embedded PLCs like robots (*WP10*), automated guided vehicles (AGVs), and XR glasses (*WP5 & WP6*), or software applications connected to add-on PLCs like TDA system (*WP0*) or AGM (air-gap measurement) system, are clients for the master OPC UA (open platform communications unified architecture) server (*WP1*) connected to MES through supervisory control system (SCADA). In detailed design, MES connection to databases (dbs), APIs (application programming interfaces), and OPC UA communication across the system are elaborated, while a data warehouse between MES and its clients is under investigation by SGRE IT infrastructure team. The lowlighted dashed areas in Figure 4, neither exist in current SGRE manufacturing nor fall within this paper's scope. Arrows represent dataflow directions.

Virtual platform/DT, platform 5 in Figure 4, contains subsystems that virtually represent real world parts. Each component (*WP3, WP4, WP5, WP6 & WP7*) offers some features to facilitate virtualisation for an optimum real-time DT to validate *changes* (out-of-threshold discrepancies). That said, if *changes* and the *impact* predicted by AI DL model (*WP9*) (Nickpasand et al., 2024a), are recognised as valid for permanent deployment (e.g., because of tool or procedure better application) and falls within the strategic threshold, the ECM (engineering change management) module in engineering platform (function 1.2.3) triggers its implementation (*WP8*) (Nickpasand et al., 2024b) by updating set-points (relevant P-set) and documents. While, temporary or trial changes (e.g., because of tool breakdown or operator's mistake) are treated as non-conformities, which are voided and archived (Nickpasand and Gaspar, 2023a).

Integrated Graph Database (*G-db*), platform 6 in Figure 4, demonstrates manufacturing system ontology, serving as architectural backbone for any system development. This platform that unifies scattered dbs is elaborated in a separate paper (under review) and used in *WP1* (for OPC UA agile information model) and *WP2* (for MES modular service-oriented logic).

In such a closed-feedback-loop architecture, MES plays a focal role in *communication* and *synergy* (in collaboration with G- db and OPC UA), while the virtual platform supports *emergence* and *evolution* through simulation and AI models. These four characteristics of a system of systems (SoS), per IISO/IEC/IEEE 21839, 21840, 21841:2019 (2019), represent inherited fundamental system properties (ilities) enabling response behaviour in manufacturing (Nickpasand and Gaspar, 2023b). In agility design full implementation, *evolution* refers to learning, remembering, and prediction abilities, *emergence* refers to collective system behaviour, and *synergy* refers to harmonised and synchronised reconfiguration – all resulting from component interactions within the system whole. DT and MES, combined with technologies supporting response-driver ilities (Ross and Rhodes, 2015), contribute to both reducing response time and data-driven decision-making in response to changes, enhancing responsiveness, thus ultimate agility.

3.3 Technology assessment and project planning for SGRE OWT manufacturing agility portfolio

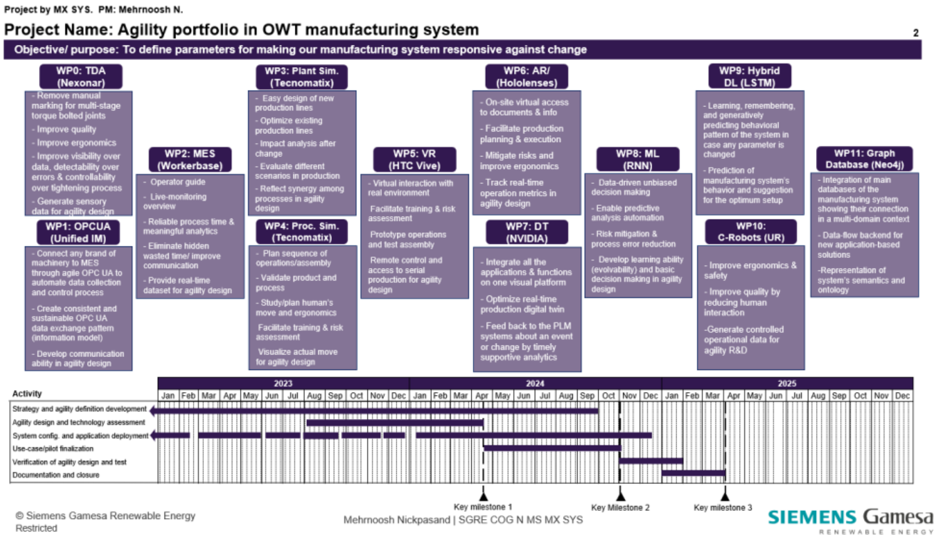
A thorough commercial-off-the-shelf (COTS) market investigation and technology assessment proposes alternative software solutions for each technology WP in SGRE agile manufacturing portfolio, Figure 3 prioritising existing SGRE systems to reuse. For each solution, an SGRE use case is defined as a pilot project to meet individual objectives while serving as PoC for SGRE agile manufacturing. The PoC, demonstrates solution feasibility, tests core functionalities in a controlled environment, identifies risks and practical challenges, while providing insights guiding subsequent implementation phases.

Even if the ultimate agility architecture cannot be validated due to cybersecurity restrictions and data accessibility challenges through interfacing business applications, metrics are established through WP pilots to show solution effectiveness. These metrics focus on response time reduction and increased response effectivity, which can be amplified by each WP in an integrated system like the closed feedback loop in Figure 4. The PoC of the proposed system integration solution, actuated by WPs pilot implementation, will demonstrate that existing manufacturing can be more responsive when enabled to well detect unpredictable perturbations on right time (*WP0* & *WP10*), well communicate with right sub-systems (*WP1*), well interpret them in connection to other system variables (*WP2-WP6*), well predict effects and analyse impacts (*WP7-WP9*), well decide optimal responses (*WP8 & WP9*), well implement responses throughout the entire system (*WP2*), and well reconfigure accordingly (*WP1 & WP11*).

PoC use cases for each WP are appointed based on strategy, business, and field input, with technology assessment narrowed to SGRE-specific solutions. Some WPs (e.g., MES in *WP2*), use external suppliers for software development, while others (e.g., OPC UA in *WP1*) reuse infrastructure from existing SGRE projects (e.g., machine connectivity – IRIS). Systems with existing licenses (e.g., Tecnomatix Plant Simulation in *WP3* (Nickpasand et al., 2025)) or hardware (e.g., XR glasses in *WP5 & WP6*, or C-robots in *WP10*) are prioritised for standardisation of utilisation. Solutions like AI models in *WP8* and *WP9* or G-db in *WP11* are developed in-house for specific SGRE use cases, with numerous collaborations across automation, digitalisation, and robotisation projects.

In this agility R&D project, portfolio management follows SGRE project management structure, with the high-level portfolio schedule shown in Figure 5. The figure reflects WPs by concept names, types, and objectives, with timeframes and milestones for the overall agility project activities.

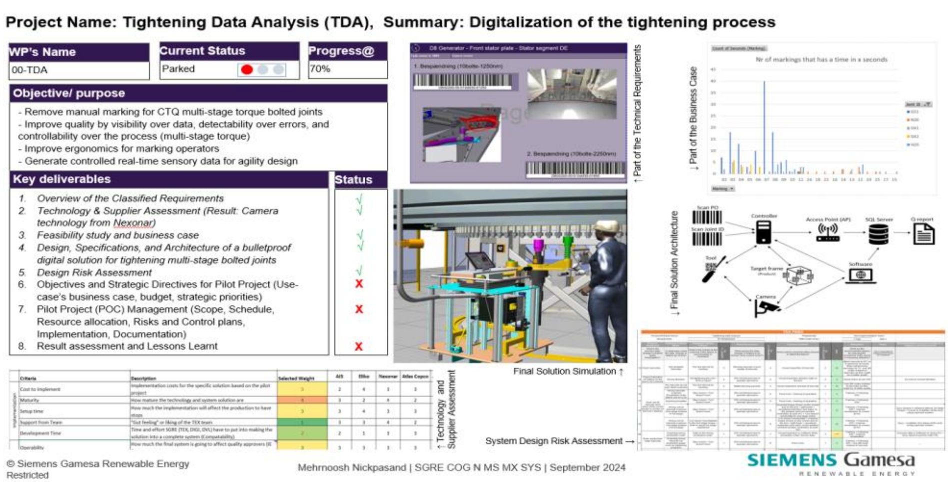
Figure 5 Portfolio management structure and the high-level schedule (see online version for colours)



3.4 *WPs development and pilot projects implementation for SGRE agile manufacturing in practice: WP0 as an example*

Following SGRE project management structure, each WP of the portfolio has gone through the development framework pipeline, while eight deliverables (highlighted in Figure 3, right) are reported during progress, with WP0 exemplified in Figure 6.

Figure 6 Exemplified WP development and pilot implementation progress report, WP0-TDA (see online version for colours)



This figure shows WP0, digitalisation of bolted joints tightening process and its data analysis (TDA), with development and pilot implementation progress reported in a project one-pager template. The template displays project status at top left, followed by

WP objectives as baseline. Eight deliverables from the portfolio development framework, Figure 3, right, are listed with their corresponding status. The template includes samples and screenshots of project content with hyperlinks for detailed access.

Figure 6 displays technical requirements for a two-stage bolted joint (as a part of delivery#1), technology assessment using weighted scoring for four suppliers (delivery#2), business case excerpt (delivery#3), system specifications (delivery#4), and system design risk assessment using D-FMEA (design failure mode and effect analysis) format (delivery#5). The centre displays a simulated model screenshot with hyperlink.

This WP, as a digitalisation solution for tightening multi-stage torque bolted joints, individually aims to remove manual marking, improve quality by ensuring proper bolt tightening, and enhance operator ergonomics, who are currently marking the bolts manually. While in agility architecture, this solution generates real-time sensory data for MES through its OPC UA-compatible hardware (torque wrench tools) and SGRE IIOT-ecosystem-friendly software. It develops system properties (ilities) including data visibility, error detectability, and process controllability for multi-stage torque bolts, facilitating agility in detection and risk analysis. The solution also enables learnability through quality data production, predictability via process data analysis, scalability through system modularity, and synchronisability (Nickpasand and Gaspar, 2023b).

This template is used to report the progress of each WP implementation, and principles for developing WP solutions must comply with both individual success criteria and agility integrated design.

3.5 Final design and interface analysis

Following the portfolio framework in Figure 3, right, the processes and practical steps, described for WP0 development and pilot implementation project in Figure 6, are conducted for all WPs defined in the agile manufacturing portfolio in Figure 3, left. Results are documented as scientific papers, either published, such as DT (Nickpasand and Gaspar, 2023a), agile simulation (Nickpasand et al., 2025), ML (Nickpasand et al., 2024b), and LSTM DL (Nickpasand et al., 2024a), or under review (including MES, OPC UA topics).

Figure 7 is a display of these results showing parts of implementation achievements for each WP. At left, SGRE manufacturing system G-db overview (top), MES system design architecture (middle), and RNN ML model through input generation, model’s architecture, and learning assessment result (bottom) is presented. The middle displays NVIDIA Omniverse hardware requirements (top), AR solution assessment (second top), C-robot programming (second bottom), and LSTM DL architecture (bottom). At right, 3D simulation of SGRE OWT generator production line (top) with its VR (virtual reality) view (middle) and integrated OPC UA use case (bottom) are traceable.

During PoC WPs implementation and integration risk analysis, the agility high-level architecture (Figure 4) is modified. The complete detailed design is not presentable due to SGRE confidentiality protocols. But an example is the data flow between MES and virtual platform (simulation) with a closeup in Figure 8, right, that causes modification in virtual platform setup, shown in Figure 8, left (as a cut of Figure 4).

Figure 7 Results and documentation of agile manufacturing portfolio WPs development and pilot implementation, partly on display (see online version for colours)

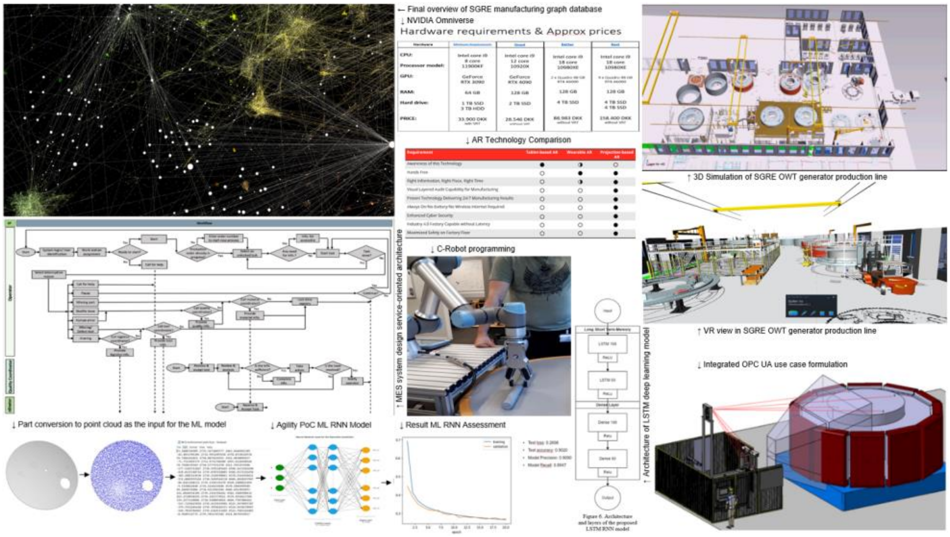


Figure 8 Agility design modification, left, according to MES-plant simulation interface analysis, right (see online version for colours)

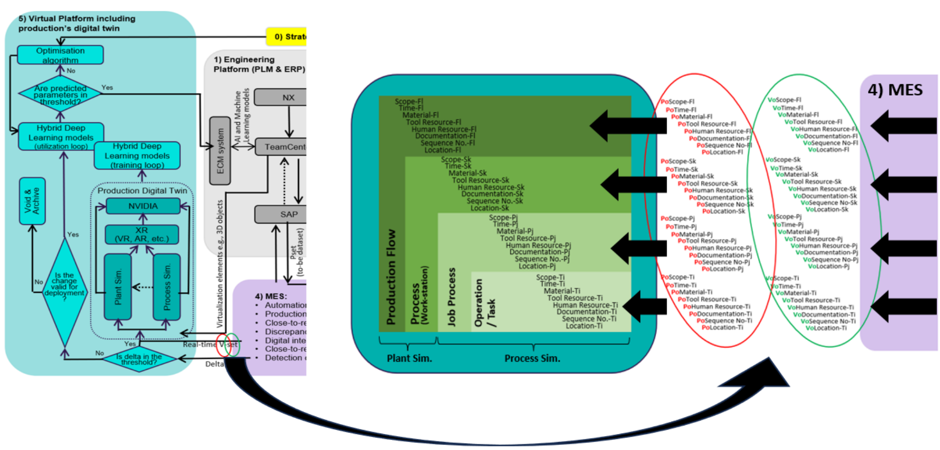


Figure 8, right, shows the interface between MES and the simulation system (main module in virtual platform), Figure 8, left. In this closeup, production flow and its process layers from Figure 2, bottom (platform 3, production environment) represent the content to be simulated. Tecnomatix Process Simulation models tasks and job processes, while Plant Simulation focuses on processes in and above the workstation layer. Eight determinant parameters at each layer define process specifications in the simulated production flow model, forming the foundation for its real-time DT.

These parameters are measurable using metrics to trace changes, shown as parameter of (Po) in red. They can be defined in MES database or other environments like data warehouses (preferably time-series databases for change tracking). Currently SGRE, with Siemens Energy, is designing a data warehouse for broader purposes, which can contain these parameters in structured format between MES and virtual platform. These parameters receive real-time values from MES, shown as value of (Vo) in green, Figure 8, right. MES collects real-time data from field clients through OPC UA.

Based on these details, the agility closed loop scenario, Figure 8, left, involves a real-time data stream feed (real-time V-set) from MES that runs the real-time simulation and DT (dashed area). This DT mirrors the production line in time, including blockages, stoppages, and flow hiccups, and remains locked against manipulation, while its outcome trains the DL model, LSTM, to learn production's behavioural pattern for further predictions.

The other input for virtual platform from MES is Delta, defined as the deviation between the P-set (to-be dataset) and V-set (as-is dataset). If such deviation, i.e., Delta, does not fall within the defined threshold, then the DT sends a pop up on its UI to ask if the detected change is temporary or permanent. In this case, the term temporary is defined as an incident, breakdown, test, or temporary fix, which is not valid for permanent deployment, and the term permanent means whatever change that is made by intention in favour of the production performance and is valid to be deployed in the system permanently. A temporary change is voided and archived or registered if such a procedure is defined for it. But a permanent change activates the DL utilisation loop where the model predicts how the change affects the production and what would be the reaction of the flow, by its parameters, to such a change.

The other input for virtual platform from MES is Delta, defined as the deviation between P-set (to-be dataset) and V-set (as-is dataset). If Delta exceeds the defined threshold, the DT sends a pop up to ask if the detected change is temporary or permanent. Here, temporary means an incident, breakdown, test, or temporary fix, which is not valid for permanent deployment, while permanent refers to intentional changes made to improve production performance. A temporary change is voided and archived, but a permanent change activates the DL utilisation loop where the model predicts how the change affects production and how the flow reacts through its parameters.

For example, material shortage may cause job sequence changes, increasing the process critical path's time and cycle-time (a deviation outside the threshold and supposedly, not temporary). The DL model may predict that adding five operators and two torque tools can maintain delivery time. Three operators and two tools can be moved from another line, but strategic directives prevent hiring two more operators, causing the DL prediction to exceed the threshold. As shown in Figure 8, left, strategic limits and DL model outcomes are inputs for the optimisation algorithm to optimise the function (cycle-time or cost function) and generate new predictions. This continues until predictions meet the threshold, when ECM system automatically takes over the final parameters and deploys the reconfiguration. Human intervention can be programmed in the loop if needed.

3.6 Agility quantification over time

In agility qualitative analysis (Nickpasand and Gaspar, 2023b), the system's actual status remains unchanged during the first three response episodes: detection (D), interpretation (I), and computation or decision-making (C) from DICEA model. It only changes when execution (E) and adaptation (A) episodes begin. Response, as a different term from reaction, occurs when the *new status* (*Sb*) equals or exceeds the *previous status* (*Sa*). System status is commonly defined by manufacturing outcome function (unit cost, throughput, or cycle-time), with the difference between Sb and Sa known as manufacturing setup *reconfiguration*.

Making an effective response (*reconfiguration*) while maintaining or improving status requires *effort* (resources) measured in man-hours, convertible to cost metrics. Minimising man-hours maximises responsiveness, defining agility as high-responsiveness and an optimisation problem. To examine this, we focus on the production segment of the manufacturing system.

The initial system status (Sa) for a production line (Fl) is an array comprising eight parameters shown in Figure 2: scope-Fl, time-Fl, material-Fl, tool resource-Fl, human resource-Fl, documentation-Fl, sequence number-Fl, and location-Fl, numbered $n = 1–8$ correspondingly. Status change from Sa to Sb occurs when parameters exceed thresholds, or their combinations violate predefined constraints.

Below optimisation problem aims to minimise total man-hours for system reconfiguration from Sa to Sb, subject to Sb greater than or equal to Sa, with hypothetical constraints. The formulation uses mathematical notation and LaTeX commands, with Fl notation removed from indices for simplification.

Variables

- *(Sa = [sa_1, sa_2, \ldots, sa_8])*: Current status of the system
- *(Sb = [sb_1, sb_2, \ldots, sb_8])*: Target status of the system, with (sb_i \geq sa_i)
- *(MH_n)*: Man-hours required to change parameter (n) from (sa_n) to (sb_n)

Objective function

[\text{Minimise } MH{\text{total}} = \sum{n = 1}^{8} MH_n]

Constraints

1 Status Constraints:

- [sb_n \geq sa_n \quad \text{for all } n]

2 Parameter-Specific Constraints:

- **Scope:** (sb_1 = f(\text{production requirements}))
- **Time:** (sb_2 \leq \text{maximum allowable production time})
- **Material:** (sb_3 \leq \text{available material inventory})
- **Tool:** (sb_4 \in \text{available tool set})
- **Human Resources:** (sb_5 \leq \text{available operators})
- **Document:** (sb_6 \in \text{approved documentation set})
- **Sequence No.:** (sb_7 \text{follows predefined sequence logic})
- **Location:** (sb_8 \in \text{approved location alternatives})

3 Threshold constraints:

- Triggered by out-of-threshold changes in parameters: (\Deltan > \Delta{\text{threshold}})

4 Logical constraints:

- Dependencies between parameters, for example:

  If (sb_4) (tool) changes, (sb_3) (material) and (sb_5) (HR) may also need adjustment.

In LaTeX, **\text{}** formats text within mathematical expressions, serving as plain text labels to indicate objectives and constraints as **(\text{Minimize})** and **(\text{Subject to})**. **(\geq)** is a LaTeX command for 'greater than or equal to', while **(\leq)** represents 'less than or equal to'. **(\quad)** is spacing command, and **(\in)** means 'element of' showing a value belongs to a set.

An exemplified constraint can be if the scope ((sb_1)) expands, the material ((sb_3)) and time ((sb_2)) must increase accordingly:

[sb_1 > sa_1 \implies sb_3 > sa_3 \text{and} sb_2 > sa_2]

Or if a new location is required ((sb_8)), ensure it is within the approved alternative list and accessible to required tools:

[sb_8 \in \text{approved location list} \text{and compatible with} sb_4]

This formulation provides a general shape of the optimisation problem to define agility as high responsiveness based on effort required to revise system setup during response to out-of-threshold parameter changes. The formulation is adaptable by integrating domain data and specific constraints. By incorporating historical data and detailed criteria, the constraints will be refined, and the problem can be solved using optimisation techniques like linear programming or mixed-integer linear programming (MILP).

As explained in section III-C, ultimate system agility could not be measured here by the proposed architecture due to challenges with data accessibility and cybersecurity restrictions at interfacing business applications. To minimise reconfiguration man-hours, each technology in the agility portfolio, Figure 3, left, contributes to reducing reconfiguration time or effort by increasing response effectiveness. Section 3.3 describes how each technology solution (i.e., WP) contributes to this optimisation problem by bringing transparency, analysis, and control over manufacturing parameters. Further analysis will determine which solutions are agility enablers (must-have) vs. enhancers (nice-to-have) in system design.

4 Results and input for further upscaling phase

The result of the agility research and its portfolio PoC implementation is reflected in Figure 9, where the first five columns (area A bordered in Red) identify the concept, problem addressed, proposed technology solution, individual outcome and benefits, and implementation use case. For example, to respond agilely to complex and frequent changes in SGRE manufacturing (Col. #2), the first step is realising agility parameters (Col. #1). Hence, agile system characteristics are identified (Col. #4) by analysing response behaviour in industry context (Col. #3), where high-level requirements for agile system engineering are recognised as system properties (i.e., ilities). By developing these ilities for a small scope tightening system, as a use case (Col. #5), the agile system concept is validated through shortened response time.

Figure 9 Agility development and portfolio implementation results as input for further upscaling phase (see online version for colours)

General overview of the WPs defined in SGRE agility technology portfolio

		Concept	Problem in focus	Proposed solution	Individual outcome and benefits	Use case	PoC current progress	Roadblocks (Pilot scope)	Agility enabler or enhancement?	Priority of deployment	Success Criteria	MOE (measure of effectiveness)	Relevant publication	Presented or published at
Agility for SGRE OWT Manufacturing System	Agility Definition	Agility as High Responsiveness; Parametric Definition	What agility means and how to respond agilely to complex and frequent changes in manufacturing system (effective and quick enough response)	Analyse response behaviour, Reflect the analysis on industrial context, Classify "ilities" (the properties that the system should have to be responsive), and Define the parameters of such responsiveness	Agility parameters and agile system's characteristics for directing the focus and investment	How to identify and develop the lacking properties of an agile tightening system A	100%	Lack of quantitative research B	Nice to have C	–	Effective methodology for such analysis D	Improvement in agility by reducing the response time in a small exemplified system	"Ilities for Responsive Manufacturing: A Case from Offshore Wind Turbine Manufacturing" E	18th International Conference of System of Systems Engineering (SoSe), Lille, France, 2023
	Agility Design	Agility Design and Framework for SGRE	How to become agile	Application of System Engineering principles and methods to design an agile manufacturing system, identify elements, and develop them	A framework and guidelines for "getting agile", from feasibility study phase to documentation and closure, (an SGRE standard, reusable for any operation-based industry)	How to use the framework in development of an agile manufacturing system, whereas the increase of system's agility is visible	90%	Lack of IT support to connect subsystems and verify the system design	Must have	0	Design of an agile system that meets SGRE's specific requirements	Verified improvement in system agility by reducing response time toward a common frequent change example	Agility Design; A Framework for Offshore Wind Turbine Manufacturing System	Under Development
Technology Portfolio (Enabling Agility in SGRE OWT Manufacturing System)	Digital Solution	WP0: Tightening Data Analysis (TDA)	Lack of visibility over data, detectability over errors, and controllability over the process of tightening bolted joints to facilitate an effective response and reduce response time. And, lack of high-quality data for further analytics in agility loop	Laser-camera tool tracking system to control the coordination of the tool vs. the joint's position at each tightening stage	Improvement in ergonomics and quality of bolted joints, as well as remarkable time-saving by replacing the manual marking system with a digital system for multi-stage tightening bolted joints	Tightening process of N20 bolted joint	70%	The project's ownership is given to the digitalization team	Nice to have	–	Meet the requirements for removal of marking upon approval of the 1st-level stakeholders	No red risk (higher than 200 RPN) in D-FMEA for the quality-relevant processes	–	–
	Interconnectivity &	WP1: Open Platform Communication Unified Architecture (OPC UA)	How to communicate with the real world (collect or send data from/to tools, machinery, and UIs) digitally, while if any change happens in the information flow pattern, the system updates automatically	OPC UA deployment to enable meaningful communication among all the software and hardware (by any brand and distance) through cybersecurity protocols. The OPC UA information model (IM) to be connected to the graph db for automatic update	Integration of MES and all the workstations, including people (through UIs), tools, machinery, and transporting devices (already under deployment by IRIS and OneMES Machine Connectivity workstream) with graph db-coupled IM	MES connection to Photo-shooting Robot at segment-to-segment connection workstation in generator line collecting airgap prediction measure	60%	The prerequisites for final verification should be provided by IRIS and IT infra.	Must have	3	OPC UA agile connection between MES and a field device (robot) compliant to SGRE under-development OPC UA framework	Visible real-time update in OPC UA connection when the airgap prediction formula is updated by TE	Consistent Open Platform Communications Unified Architecture (OPC UA) in Support of Agility; A Case from Offshore Wind Turbine Manufacturing	Under review by Journal of Industrial Information Integration
	Execution System	WP2: Manufacturing Execution System (MES)	Lack of a digital interface for all the subsystems in an integrated, consistent, and responsive system where both the intended outcome and the real-time status are visible	A modular MES architecture, agile in content and connections to other subsystems, to verify the visibility, reliability, and integration of the system, as well as providing live data stream for the Digital Twin	An established standard methodology for the development of a modular MES, where both the content and its connection to other subsystems are agile toward changes	MES for integration of 3 workstations in BDK MKIV Generator production line (with result of over 75% effectivity on all the 5 success criteria)	100%	Neither the methodology nor the novel aspects are considered or reused in the upscaled/global scope	Must have	2	Agile modular MES process-based backend, able to be updated automatically if any changes happen in master data or SAP ERP process model)	No red risk (higher than 200 RPN) in D-FMEA for the execution-relevant processes	Manufacturing Execution System as a Key Enabler for Agile Manufacturing; A Case from Offshore Wind Turbine Manufacturing	Under review by Journal of Intelligent Manufacturing
	Digital Twin (DT)	Production Digital Twin (DT)	Real-time virtualization of production to bring live visibility over production sequences, dependencies, and flow to detect and trace the change footprint	Define the elements of a Digital Twin (DT), practically customized for SGRE reusing the existing technologies and business apps in SGRE (e.g., Tecnomatix simulation software, VR/AR, NVIDIA Omniverse, etc).	Introduction of state-of-the-art technologies and their benefits, standardization of their agile logic, and their connection in SGRE manufacturing context	Plant simulation of BDK MKIV/DB Generator main production line, VR of the same environment, VR of the CUX incomplete simulation, AR technology assessment and NVIDIA Omniverse body of knowledge	40% - Stopped	Lack of resource	Must have	3	Real-time virtual lab. implementation	Running real-time virtual production with life-like graphics	Digital Twin for Agile Manufacturing: Challenges from Offshore Wind Turbine Industry	37th Annual International Conference on Modeling and Simulation (ECMS), Florence, Italy, 2023
		WP3: Simulation Agile Logic	Lacking a standard framework for creation of an agile (optimum responsive) simulation	An automated logic by programming different scenarios in the Simulation software app	Development of a standard framework for creation of a responsive simulation (reusable for other simulation purposes)	Experiments in BDK MKIV Gen. and BE, and CUX MKV Gen BE production line	75% - Parked	Lack of resource	Must have	2		Reduced response time for configuration of the simulation upon change in production parameters	Offshore Wind Turbine Factory Simulation as Enabler of Agile Manufacturing	Under publication; accepted by the "Journal of Simulation"
		WP4: Process Simulation	Lack of a standard framework for creation of an agile (optimum responsive) simulation	An automated logic by programming different scenarios in the Simulation software app	Development of a standard framework for creation of a responsive simulation (reusable for other simulation purposes)	Placement and application of pre-tension torque in tightening process of N20 bolted joint	40% - Stopped	Lack of license	Nice to have	–		Reduced response time for configuration of the simulation upon change in production parameters	–	–
		WP5: Virtual Reality (VR)	Lack of a standard procedure for VR hardware/software selection compliant to compatibility and cybersecurity requirements	- Reuse VR feature in Tecnomatix simulation software - HTC Vive PRO2 system compatible with Tecnomatix	Virtual reality environment for: - Tool testing - Operators training - Ergonomics check - Process validation - Quality control	DB generator production line in BDK B14	30% - Parked	Lack of resource	Nice to have	–		Increased quality and effectivity of response to unplanned change in production parameters	–	–
		WP6: Augmented Reality (AR)	Lack of a standard procedure for AR hardware/software selection compliant to compatibility and cybersecurity requirements	Hololenses as a foundation for holography to allow the operator control the quality of the process and fill the check-list	Virtual reality environment for: - Tool testing - Operators training - Ergonomics check - Process validation - Quality control	Quality control during the assembly process + AR as UI	25% - handed over to NPI Test team	The project's ownership is given to the NPI Test team	Nice to have	–		Increased quality and effectivity of response to unplanned change in production parameters	–	–
		WP7: NVIDIA Omniverse	Lack of a standard procedure and a DT platform for integration of virtualization modules and utilization of NVIDIA Omniverse in supprt of agility	NVIDIA in connection to Tecnomatix to verify integration of virtual platform	Life-like optimized digital twin	Integration of all the digital platforms we developed under this research project	15% - Stopped	Lack of license	Nice to have	–		Reduced response time in an integrated real-time interactive virtual environment	–	–
	Artificial Intelligence (AI)	WP8: Use of AI/ML in PLM System	Time-consuming deployment of the change effect (e.g., PLM Teamcenter accountability check process during GMD creation when design changes)	Application of AI/ML model to learn the pattern of the material allocation and predict the allocation is the design change	Prediction of the impact of a design change (intelligent accountability check)	Predict the affected operation if the design change (predict material allocation after design change)	80%	Lack of IT support to develop the frontend and assess the risks	Nice to have	–	Precision over 80% Accuracy over 80%	Model recall over 80% Test loss less than 20%	Machine Learning in Agile Manufacturing; A Usecase from Offshore Wind Turbine Product Lifecycle Management (PLM) System	38th Annual International Conference on Modeling and Simulation (ECMS), Cracow, Poland, 2024
		WP9: Prediction & Optimization by AI (Deep Learning Models)	Prediction of the production behaviour upon multiparameter changes	Hybrid Deep Learning (DL) model can learn and remember the dependencies and sequence of operations in a way that when one or multiple parameters are changed, it can predict the effect on the final outcome. By adding an optimization algorithm to the loop, we can optimize the setup according to the limits. The models should be trained by a well-developed simulation	Development of a Hybrid DL model that can learn and remember the sequences and dependencies of operations, while in case of change in parameters, it can predict generatively how the outcome changes	Change of tact-time and its effect on worker allocation at each workstation (also the final number of needed workers to meet the new takt-time)	75%	Lack of time/ resources to investigate incorporation of other DL components to increase efficiency and precision	Must have	4	MSE less than 1 person, MAE less than 1 person,	RMSE less than 1 person	LSTM RNN in support of Manufacturing Simulation-based Digital Twin; A Case from Offshore Wind Turbine Production	19th International Conference of System of Systems Engineering (SoSe), Tacoma, WA, USA, 2024
	Digital Solution	WP10: Cobot	Bad ergonomics unsafe repetitive manual operations	UR collaborative robot (Cobot)	- Operations robotization - Operations precision and quality improvement - Ergonomics and safety improvement - Time saving - Controlled & high-quality data production	Cobot programming and utilization as a part of BDK warehouse automation	50%	Lack of budget to provide some enabling components	Nice to have	–	Picking accuracy over 90% Safety compliance to ISO 10218,	Efficiency rate over 85% Error rate less than 15% Integration test result: no error	–	–
	Ontology and Backend	WP11: Graph Database and Ontology of SGRE Manufacturing System	Inefficient scattered databases and their relational structure to reflect dynamic change	Graph database meets the requirements and reflects semantics of the system and meanings of the connection between the systems	Structured overview of all the connections between system's entities and their content, less space (either on servers or cloud), and data-flow backend for applications development	Proof of concept as a limited database for MX Sys. team	20%	Lack of resources	Must have	1	Ontology of manufacturing processes covering 100% of key workflows and relationships among data points	Data sources integration rate over 50%, Query performance, System load handling	–	–
Admin.	Framework	WP12	Lack of a framework for system engineering R&D projects	Package of step-by-step guidelines, projects' documentation, and templates	Saving time and cost spent on unstructured try-and-error experiments	Scattered PoC projects	30%	Lack of resources	Must have	5	Portfolio strategic alignment over 90%, Projects success rate over 70%, Project documentation over 70%, Meet innovation metrics	Performance tracking structure, SGRE project management framwork alignment, Resource utilisation metrics	–	–

Columns #6 & 7 (area B bordered in Green) reflect project management concerns regarding pilot implementation progress and roadblocks. In Row #2, the agile design pilot system is at 90% progress (Col. #6) but faces delays due to insufficient IT support for subsystem connections (Col. #7).

Columns #8 & 9 (area C bordered in Blue), Figure 9 address managerial concerns regarding investment in these technologies, their necessities and priorities. These columns indicate whether concepts are must-have (enabler) or nice-to-have (enhancer), and their investment priorities (to secure prerequisites during implementation). For example, Rows #5 & 7 indicate that MES and Simulation with agile logics (WP2 and

WP3) are essential enablers with second priority in investment and implementation, after the prerequisite graph database and SGRE manufacturing system ontology in WP11 (first priority in area C).

System engineering perspective is reflected in columns #10 & 11 (area D bordered in Orange), defining success criteria and measure of effectiveness (MoE) for each WP project. For example, for MES in WP2 (Row #5), the success criterion is an agile modular MES backend that updates automatically when master data or SAP ERP process model changes (Col. #10). Column 11sets the main design MoE as having no red risk (above 200 RPN) in D-FMEA for execution-relevant processes.

The last two columns (area E bordered in Purple), share information about results documentation and publication. The AI ML model development in WP8, Row #12, for example, is documented in paper (Nickpasand et al., 2024b) presented at the 38th annual International Conference on Modelling and Simulation (ECMS), Cracow, Poland, 2024.

In Figure 9, the first two rows establish SGRE agile manufacturing foundations, while subsequent rows overview WPs as architectural elements. DT concept (Row #6) comprises different WPs and is reflected with its benefits. The last row represents administration WP for portfolio management.

From Figure 9, the main architectural elements and agility enablers, in implementation priority are:

1 agile process definition in ontology or G-db format for scaling

2 MES with agile backend

3 DT with agile backend

4 OPC UA with agile information model

5 AI learning models where data is available to predict changes or their impact.

5 Concluding remarks: expanding the agile framework in practice

The proposed agile design framework for OWT manufacturing integrates system engineering principles and technologies to enhance manufacturing system responsiveness. By leveraging SoSE methodologies, the framework creates an architecture that supports interoperability among digital tools and improves communication among subsystems. Implementation of a MES and Digital Twin (DT), along with AI learning models and Open Platform communications Unified Architecture (OPC UA) based on a consistent dynamic ontology backend enables real-time data analysis and decision-making. These technologies cultivate capabilities and system properties (ilities like interoperability, evolution, emergence, and synergy) in manufacturing system anatomy and contribute to overall responsiveness in a closed feedback loop. Pilot introduction of these technologies into SGRE OWT manufacturing system shows a 10–12% response time reduction (in each WP scope) and visibly improved response quality (precision, accuracy, and effectiveness), measured by domain metrics in each WP. Findings aim to facilitate a high-performance manufacturing system capable of responding swiftly to unpredictable changes while maintaining operational excellence.

The approach used in this research, though, even if trying to be comprehensive and pragmatic, has limitations. Technology headlines and assessment criteria may change with shifting strategies and business priorities. The approach itself should follow agility principles through an agile administration framework in WP11. Technologies with high dependencies (e.g., NVIDIA Omniverse) may not be properly assessed in a limited R&D framework, while additional WPs in the portfolio could facilitate interfacing possibilities and optimise the architecture. To address this, an innovation R&D lab with a dedicated budget for continuous research has been proposed to SGRE management for evaluation.

Still, this research provides a foundation for further upscaling and implementing the proposed agile manufacturing system, while serving as a guideline and roadmap for a smart factory evolution. However, the multidisciplinary approach in this research requires a comprehensive program management at upscaling phase that, in practice, may create strategic conflicts. Distributed ownership of disciplines, interdisciplinary budget limits, resource competency management and allocation, partial system reengineering requirements conflicting the running system, and interface risk analysis are key challenges during deployment. Besides, the program deployment timeframe across SGRE OWT manufacturing factories in different geographic locations with different infrastructure, may span years, adding complication and risks over time. During this period, technologies may up/outdate, and disciplines may reorganise (what happened during this research) while agreements deviate from their objectives.

To mitigate complexity, three scenarios are proposed to SGRE Nacelle management: First, deploy the overall architecture in an existing live factory setup as an agile pilot and ramp it up gradually before full global expansion. This was the initial research PoC objective, but IT obstacles, reorganisations, and limited strategic support prevented implementation. The argument remains valid to reuse existing infrastructure in a running production with mature process definition and stable parameters to develop a pilot and identify risks. This scenario, however, may incur higher costs and risks than initially estimated, for instance, in case of tool refurbishment for OPC UA compatibility or production stoppage during MES implementation.

The second proposed scenario involves deploying the concept progressively during new product model ramp-up in a new factory. So, the deployment cost spreads over the ramp-up timeframe (some years), with everything designed from scratch to meet requirements, while risks can be identified without impacting ongoing processes. However, expert resources must remain longer, increasing costs, and system development must align with process and product development which increase risks and challenges in resource management. Process definition and parameters can only be finalised when product design is complete, affecting material flow, layout, and production parameters. MES, OPC UA, and Simulation development require mature-enough process definition, while training AI models need real-time data availability. This dependency on product and process maturity makes this scenario risky.

The third scenario proposes modular distributed deployment, with distributed ownership of architectural elements by relevant functions or departments (e.g., IT, tooling, Operational Excellence). In this scenario, deployment costs are distributed across budget categories, with experts assigned from relevant domains. However, managing modules with scattered ownership under one program is challenging. This requires comprehensive program management with Enterprise Architecture mandate to coordinate across disciplines and raise legitimate demands. Creating a common timeline for development and deployment is difficult, with high risk in interface management.

These scenarios were assessed on Cost, Time, HC (headcount), and risk factors, with scores averaged, normalised, weighted, and summed for each scenario. SGRE Nacelle management gave the lowest score to the first scenario, which was selected as the next practical step.

Development in this research is applicable across the SGRE OWT value chain phases, Figure 2, top, although parameters like environmental factors differ. Technology assessment for site installation and offshore operations shows similar technologies can accommodate the concept in various environments (e.g., offshore, climate-specific sites, different factory locations).

Environmental factors and manufacturing complexity do not affect the approach's applicability if:

1. processes and ontological relationships are well defined to shape the agile backend for any software application and information model
2. communication between subsystems is well established to collect real-time data and timely activates subsystems for proper response
3. a digital interface integrates manufacturing phases and detects deviation between intended content and real-time values
4. value-adding processes are virtualised, and at least simulated as the ground truth, to reflect a twin of the real-time running factory and provide test environment
5. AI learning models support complex analysis and decision making.

On the foundation of such insight, the principles and methodologies used to develop an agile design for assembly manufacturing are also applicable to other manufacturing systems outside SGRE, provided infrastructure like PLM and ERP systems exists with defined data governance. However, for new factories, developing a system lifecycle corresponding to the PLM system can enable harmonious product, process, and system development. Response time, for cyber-physical complex systems like smart manufacturing affects business competitiveness, and without integrated architecture converging technologies and enabling harmonic behaviour, consequences may be irreversible.

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Conflict of interest

All authors declare that they have no conflict of interest.

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