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INDUSTRY ARTICLE

Implementation of a holistic digital twin solution for design prototyping and virtual commissioning

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Abstract

Industry 4.0 has ushered in a new era of digital manufacturing and in this context, digital twins are considered as the next wave of simulation technologies. The development and commissioning of Cyber Physical Systems (CPS) is taking advantage of these technologies to improve product quality while reducing costs and time to market. However, existing practices of virtual design prototyping and commissioning require the cooperation of domain specific engineering fields. This involves considerable effort as development is mostly carried out in different departments using vendor specific simulation tools. There is still no integrated simulation environment commercially available, in which all engineering disciplines can work collaboratively. This presents a major challenge when interlinking virtual models with their physical counterparts. This paper therefore addresses these challenges by implementing a holistic and vendor agnostic digital twin solution for design prototyping and commissioning practices. The solution was tested in an industrial use case, in which the digital twin effectively prototyped cost-efficient solar assembly lines.

1 | INTRODUCTION

A traditional mechatronic system verifies and validates the system during the last step of the product development process. This is error prone and increases development costs and time to market. Hence, virtual prototyping and commissioning practices have emerged to improve system quality and test system behaviour. This shift towards virtual solutions means that commissioning can start early in the development process, as it does not require any physical asset.

Virtual commissioning is the practice of using simulation technologies to test system behaviour with a virtual model before connecting it to the real system. As a result, errors are detected early in the process, which significantly reduces ramp up and costs [1]. This requires, however, the cooperation of different engineering disciplines throughout the whole production process.

The simulation technology currently used in digital manufacturing develops system engineering in parallel with concept design. Virtual commissioning is therefore carried out jointly or sequentially with virtual design prototyping and engineering, in contrast to conventional commissioning (see Figure 1). Consequently, verification of the manufacturing system is conducted in the early design phases, as the system can be built and tested virtually without the need of its physical counterpart. [1]. This significantly improves the design and the overall quality of the new systems.

Three possible alternatives to address virtual commissioning have been proposed, combining real and virtual counterparts of the mechatronic system and control [2], as illustrated in Figure 2.

Reality-in-the-loop (RiL) most closely reflects conventional commissioning in that a simulated control system is used to test the physical mechanical system [3]. In this system, commissioning cannot be achieved until the real system is in place. Hardware-in-the-loop (HiL) and Software in-the-loop (SiL), on the other hand, present significant advantages in terms of time and solutions to setbacks that could occur before

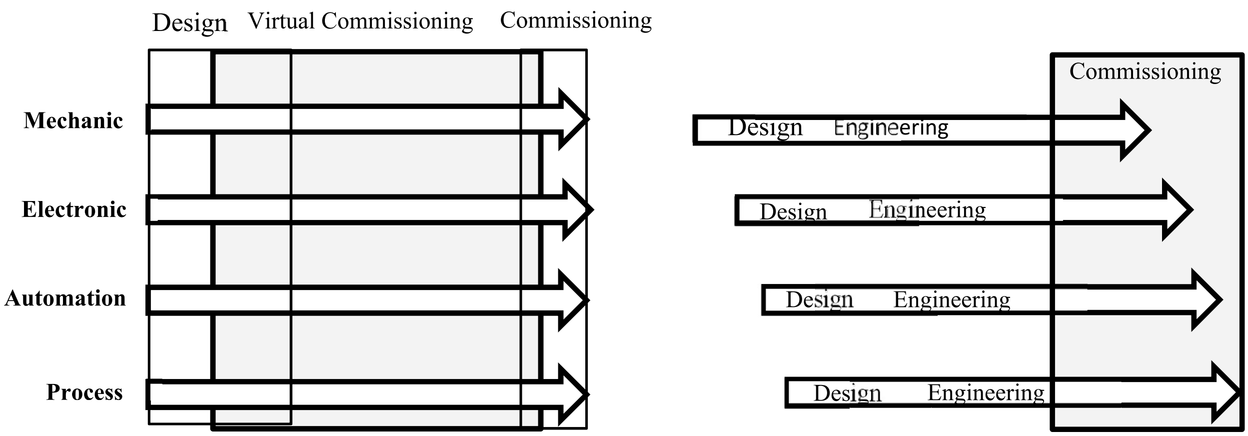

FIGURE 1 Virtual commissioning versus conventional commissioning

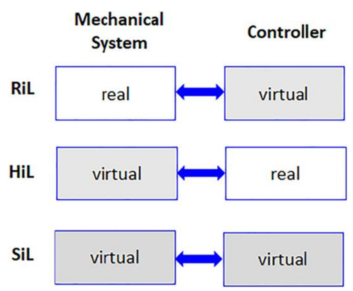

FIGURE 2 Virtual commissioning alternatives

the final commissioning phase [4]. HiL systems use a model to simulate the response of the real mechanical system and are driven by a real controller. By replacing the mechanical system with its virtual version, the control software can be tested in the early phases. SiL goes one step further, employing both a virtual control system and a virtual mechanical system. The speed of the simulation can therefore be faster or slower depending on the aim of the tests. At faster speeds multiple tests can be rapidly conducted, and complex systems can be tested at lower speeds.

Commissioning alternatives are on the rise with the introduction of Industry 4.0. This new digital era has brought new technologies such as the digital twin to enhance the virtualisation of factories. The digital twin is considered the next wave in modelling and simulation, which can further boost virtual commissioning practices. It is a virtual replica of the production system, and hence, involves an operational system. The existing physical system and its digital replica are fully synchronised in both directions, and thus the digital model reflects the behaviour of the existing system. This addresses any inconsistencies between the digital model and the physical system [5]. While virtual commissioning consists of multiple simulation technologies mostly commissioned in silos by different engineering disciplines, the digital twin integrates all of these into one platform. This, however, requires a holistic environment that integrates different vendor specific tools.

A number of authors have explored simulation technologies in a machining context. Y. Altintas [6] presented a comprehensive review of machine tool simulation technologies (machine kinematics, structural dynamics, and control techniques). S. Rock [7] also proposed a Hardware-in-the-loop simulation scenario for virtual commissioning of machine tools. However, these solutions require the integration of partial simulation models, and lack a unified platform.

Hence, it can be seen that despite the wide variety of tools and technologies in the market, there is still no solution in which different simulation domains and the controller are integrated into a single and unified platform. Companies are therefore reluctant to invest in simulation technologies for virtual commissioning, arguing that efforts to generate simulation models are not justified in terms of Return on Investment (ROI). This has become a major barrier to establishing and adopting virtual solution strategies.

This paper, therefore, presents a digital twin-based holistic solution for virtual design prototyping and commissioning. The digital twin is built on an interoperable gateway that facilitates a collaborative environment throughout the whole development process.

2 | LITERATURE REVIEW

The digital twin first emerged as a concept in the 2003 work of Grieves, the Product Life-cycle Management (PLM) [8]. The first definition of the concept, however, is attributed to NASA in 2010: 'an integrated multi-physics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin'.

The digital twin aroused widespread interest with the introduction of Industry 4.0 into manufacturing. Figure 3 presents the results of the literature search in Web of Science (WOS) and Scopus by using the word 'digital twin' and 'manufacture*' as keywords, from 2010 to 2022. The results show that the concept of digital twin was not widely exploited until 2016 in the manufacturing field. Likewise, the number of

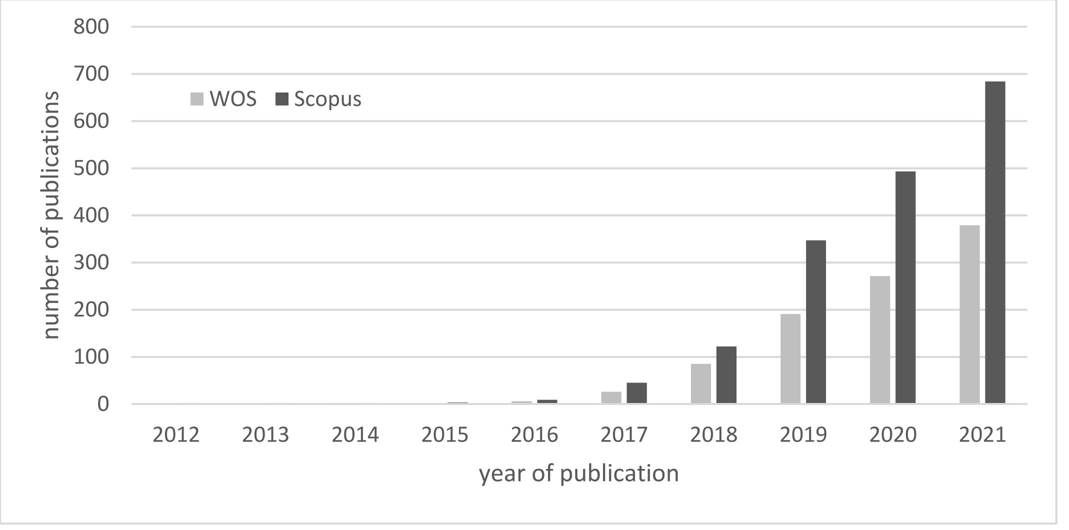

FIGURE 3 Digital twin and manufacturing related publications in literature

publications related to the digital twin has exponentially increased since then.

In the manufacturing industry, smart manufacturing is promoted by the integration of the digital twin, big data and services [9]. In this way, J. Leng et al. [10] introduced the digital twin for holistic control of a smart workshop. The methodology uses a decentralised self-organising strategy to coordinate manufacturing tasks and resources and an online parallel controlling for holistic decision making. This holistic concept also underpins the digital twin introduced by Uhlemann et al. [11]. These authors presented a multimodal data acquisition approach that builds a comprehensive image of the real production system of Small and Medium Enterprises (SME). The key aspect of this approach is the integration of isolated commercially available tools into a holistic solution.

2.1 | Digital twin throughout the life cycle

This section analyses the main applications of the digital twin by means of a snowballing search based on the literature review study of Jones et al. [12]. The cited applications have been classified according to the most suitable phases of the life cycle during the Development and Operational cycles of the digital twin as detailed in Table 1.

The results of the use of the digital twin throughout the life cycle are illustrated in Figure 4 and Figure 5.

Operations, Service, and Design are the phases where the digital twin is mostly employed. However, there is limited application during the commissioning phase. Furthermore, Figure 5 shows that most of the applications and use cases of the digital twin fall into 'operations' or 'development'. The former is the major field of application, and to date, very little attention has been paid to the role of the digital twin for both cycles (DevOps).

Drawing upon this field of study, in a previous work we presented the digital twin as a DevOps approach, in which it is active throughout the whole product life cycle [64]. In this way, product design, engineering, integration, operation, and service activities can be performed efficiently in an agile and collaborative environment between different departments [3] and engineering disciplines.

In the present paper, we establish a holistic solution from the very early stage of the development process that will be later seamlessly merged with the operational scenario, following the DevOps approach presented in [3]. This requires that all engineering disciplines cooperate in a synchronised way throughout the whole life cycle. In particular, this study is focussed on the development process, including all initial stages of the life cycle, that is, design, engineering, and commissioning.

3 | DIGITAL TWIN-BASED DESIGN AND COMMISSIONING

The design phase establishes the main machine concept draft based on the already defined system requirements of the CPS. This is usually carried out using a model-based approach, which is then enhanced by domain specific engineering functionalities (i.e., mechanical, electrical). Ideally, domain specific engineers should work in parallel in this phase, however, work is generally carried out in different departments with different vendor software tools. Communication between these interdisciplinary participants is difficult due to a lack of cross-domain language comprehension, hence the importance of establishing a vendor agnostic holistic solution. To succeed during virtual prototyping and commissioning practices, such a solution must include the following requirements:

- R1: Simulation platform for concept design (mechanical 3D models, automation, and control)
- R2: Holistic platform that integrates all simulation models (mechanical, automation, control, etc.) into a single

TABLE 1 Applications of the digital twin classification throughout the life cycle

Article	Application field	Development	Operations	Design	Engineering	Commissioning	Operations	Service
[13]	Planning	X		X				
[14]	Commissioning	X				X		
[15]	Forecasting, optimisation		X				X	
[10]	Controllability		X				X	
[16]	Optimisation		X				X	
[17]	Controllability, monitoring		X				X	X
[18]	Controllability, optimisation		X				X	
[19]	Controllability		X				X	
[20]	Reconfiguration		X				X	
[21]	Monitoring		X					X
[22]	Monitoring		X					X
[23]	Traceability		X					X
[24]	Training		X					X
[25]	Training		X					X
[26]	Simulation		X				X	
[27]	Forecasting		X				X	
[28]	Design	X		X				
[29]	Planning	X		X				
[30]	Safety, simulation, commissioning	X		X	X	X		
[31]	Training		X					X
[32]	Optimisation	X	X	X				
[33]	Forecasting		X				X	
[34]	Monitoring, diagnosis and prognosis		X					X
[35]	Simulation	X			X			
[36]	Design, engineering, commissioning	X		X	X	X		
[37]	Optimisation		X				X	
[38]	Design	X		X				
[39]	Reconfiguration	X	X				X	
[40]	Monitoring, forecasting		X				X	X
[41]	Decision making		X				X	
[42]	Design, engineering	X			X			
[43]	Traceability, optimisation	X	X	X			X	
[44]	Design, simulation	X		X	X			
[45]	Service		X					X
[46]	Diagnostics and prognosis, monitoring		X					X
[47]	Service		X					X
[48]	Reconditioning, commissioning	X			X	X		
[49]	Service		X					X
[50]	Optimisation	X		X				
[51]	Monitoring, optimisation, controllability, diagnosis and prognosis		X				X	X

TABLE 1 (Continued)

Article	Application field	Development	Operations	Design	Engineering	Commissioning	Operations	Service
[52, 53]	Design, engineering, Verification & Validation	X		X	X			
[54]	Monitoring		X					X
[55]	Decision making		X				X	
[56]	Design, Engineering, Verification & validation	X		X	X	X		
[57]	Simulation, design	X		X	X			
[58]	Traceability	X	X					X
[59]	Simulation, engineering, Verification & Validation	X		X	X	X		
[5]	Commissioning, optimisation	X			X	X		
[60, 61]	Reconfiguration, commissioning	X			X	X		
[62]	Engineering, commissioning	X			X	X		
[63]	Design, simulation, commissioning	X		X	X	X		

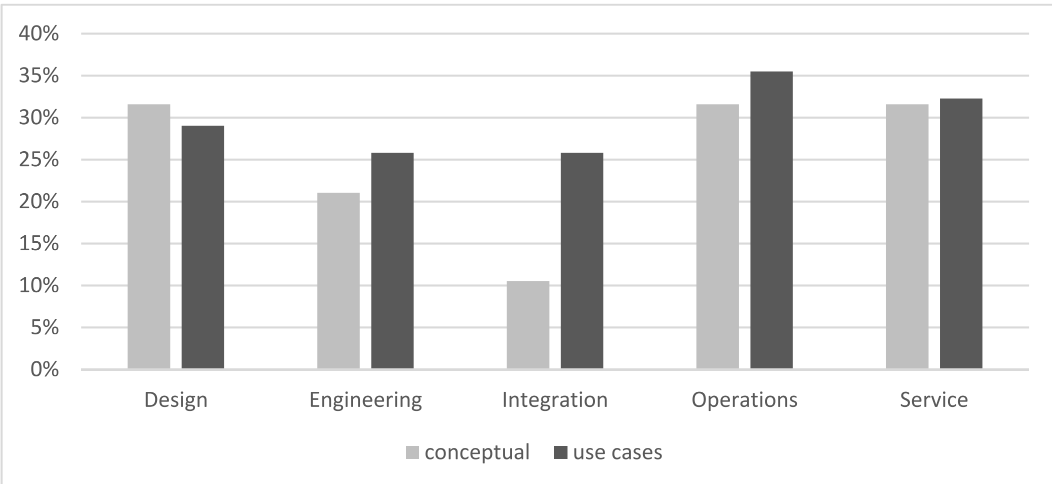

FIGURE 4 Digital twin applications throughout the life cycle

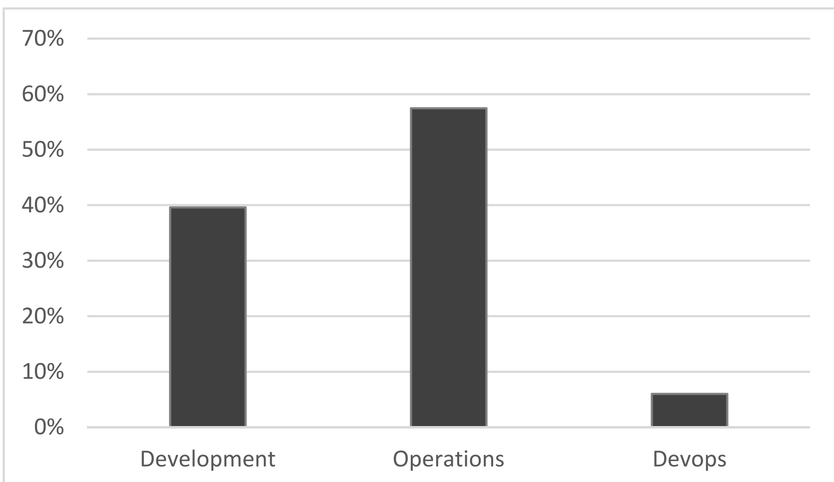

FIGURE 5 Digital twin applications classification into DevOps

environment or hardware, thereby enabling collaborative machine tool commissioning.

Table 2 sets out some of the existing virtual simulation tools in the market, and benchmarks them according to the aforementioned requirements.

The table clearly demonstrates that only one solution meets all requirements—the recently launched Siemens SINUMERIK ONE. However, this solution is vendor specific as it is limited to Siemens products. This presents a significant drawback, as there is no option to integrate components from different manufacturers.

In light of this gap, we present a digital twin-based setup that integrates vendor agnostic equipment, and simulation tools into a single and unified platform. This solution is described in detail in Section 4.

4 | DIGITAL TWIN-BASED HOLISTIC SOLUTION FOR DESIGN AND COMMISSIONING

The implemented solution holistically integrates a broad set of vendor specific tools into a single environment. Each vendor has a unique communication protocol and thus, interoperability plays a critical role. For this reason, an interoperable gateway was implemented to seamlessly integrate vendor specific controllers and simulation technologies into a collaborative platform. In this way, all engineering disciplines can easily cooperate for design prototyping and commissioning.

The solution was developed by Ideko and Mondragon Unibertsitatea, and consists of a four-layer architecture, as illustrated in Figure 6.

The physical layer is composed of multiple CPS controlled by a broad set of controllers from different vendors, which employ diverse communication protocols. These physical assets are replicated in the virtual layer with a digital twin. The virtual layer, therefore, simulates the physical controller and the mechatronic system with different simulation engineering technologies.

TABLE 2 Compliance requirements table

Tool	R1	R2
Siemens NX MCD	Yes	No
Siemens SInumerik One	Yes	Yes*
Siemens process simulate	Limited to PLC controllers	No
Siemens plant simulation	Limited to PLC controllers	No
Dassault delmia	Limited to PLC controllers	No
ISG virtuos	Yes	No
Simumatik 3D	Yes	No
Emulate3D	Yes	No
XCelgo experior	Yes	No
Visual components	Yes	No

The middleware is a communication interface that seamlessly exchanges data between the physical and virtual layers. This consists of a modular and interoperable gateway (Savvy Data Systems) that facilitates data exchange through a large number of communication protocols by using open standardised protocols (e.g. OPC UA). In effect, it translates specific protocols to open standardised protocols, to offer a solution to a wide variety of vendor specific controllers and simulation technologies (e.g. Siemens, Heidenhein, FAGOR, FANUC).

Finally, the cloud platform stores machine data retrieved from the SAVVY gateway through REST API for further data analysis and monitoring services.

5 | INDUSTRIAL USE CASE

The digital twin-based holistic solution was developed by Ideko in collaboration with Mondragon Unibertsitatea. The presented use case was implemented in Mondragon Assembly and focuses on the design prototyping and virtual commissioning of solar panel assembly lines.

Mondragon Assembly develops automated assembly solutions. The use case therefore must ensure that the required throughput of the assembly line is met. This is achieved with the use of the digital twin. The implemented holistic solution ensures that the manufacturing performance can be tested in early design phases. In this manner, layout prototyping relies on the digital model, and line throughput is calculated with synthetic data.

The solar assembly line is composed of various welding machine cells, as detailed in Figure 7. Each welding machine has a camera to determine the position of the ribbon. The welding head then calculates the trajectory of the welding process, and a small amount of flux is injected to facilitate and improve the task. Jig and fixture devices ensure the ribbon is held in place while welding is in progress. This process is repeated in each welding cell, and thus, the assembly process plays a critical role in terms of quality and performance.

Design prototyping is carried out to achieve a cost-effective control logic of the process that meets customer requirements. Commissioning early in the process is therefore crucial to improve system quality, save costs and time to market. This was achieved with the digital twin solution implemented at Mondragon Assembly.

The use case follows the architecture described in Section 4 (see Figure 8):

The assembly line was simulated in Visual Components. The logical control, however, was coupled to a TwinCAT virtual controller, emulating the physical Beckhoff controller. Beckhoff uses the ADS communication protocol to interexchange data with the logic controller. Communication was achieved through the interoperable SAVVY data gateway, which manages the data flow between all the devices. The system was built by following the steps below:

- Developing a phyton script to model the behaviour of pneumatic drives.
- Integrating the script in Visual Components.

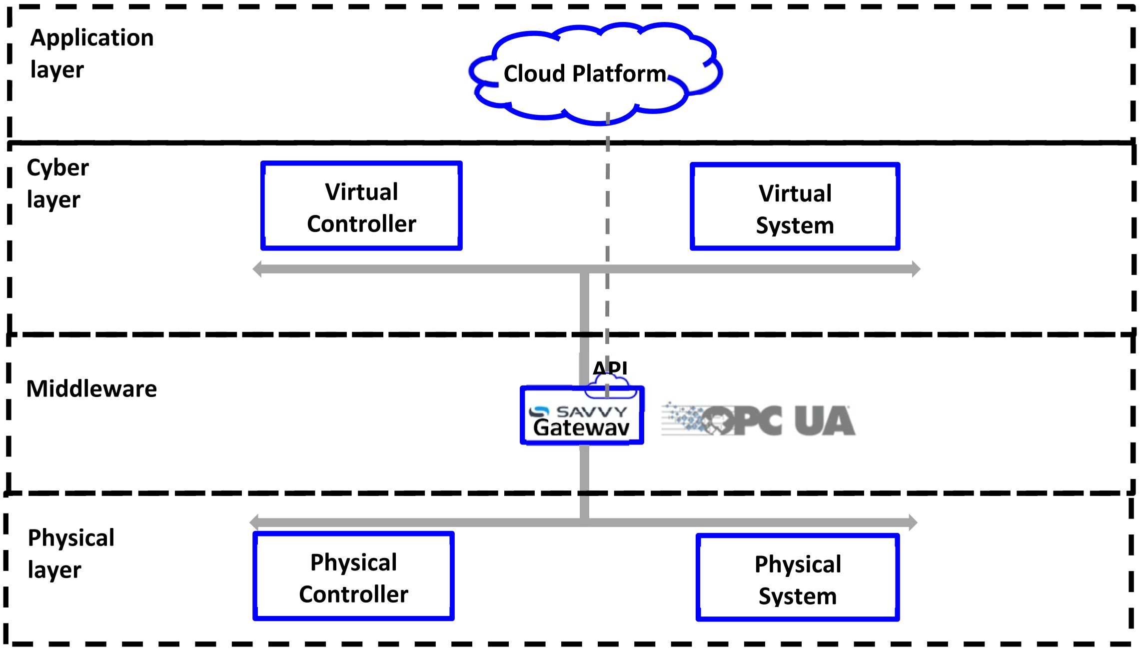

FIGURE 6 Digital twin architecture

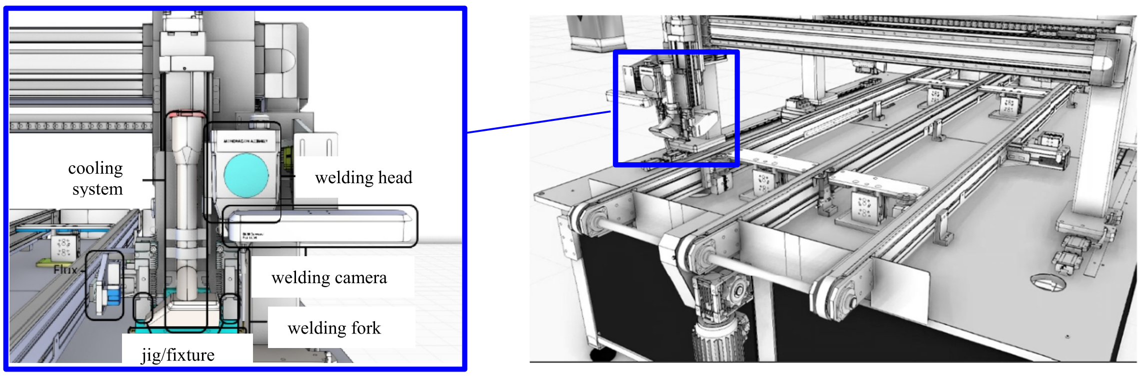

FIGURE 7 Mondragon Assembly use case - solar assembly line

- Modelling cylinder and stop sensors in Visual Components.
- Linking gantry position signals, cylinder, sensor, and stop signals of TwinCAT.
- Checking the programme cycle is executed correctly in the digital twin.

As a result, the implemented solution enables early design and verification of the system against the most demanding customer requirements. Virtual commissioning and design prototyping can be performed early in the process and a more realistic and cost effective line throughput is achieved. This is carried out in a collaborative environment between all engineering disciplines involved in the assembly process, as detailed in Figure 9.

6 | CONCLUSIONS

At present, manufacturers are reluctant to invest in virtual commissioning as there is no solution to integrate vendor specific tools into a single platform. This presents a major problem, even when building a collaborative environment with multiple engineering simulation technologies. In this paper therefore, we have presented a digital twin-based holistic solution for virtual design and prototyping. The solution was tested in an industrial use case—a solar assembly line in Mondragon Assembly, in Northern Spain—in which the digital twin was used to prototype cost-effective assembly lines. Using this solution, engineers could ensure the required line throughput was achieved, which improved the overall system performance and reduced costs.

The implemented digital twin solution offers a comprehensive tool, in which layout design and virtual commissioning are conducted in close collaboration with the corresponding engineers. As a result, engineers are able to detect issues related to 3D mechanical design, electrical design, control logic, and processes early in the development process. This can justify the ROI, enable a collaborative virtual commissioning environment, and in turn, reduce time to market and costs.

In future lines, the developed digital twin solution could be extended for use in the operational scenario by following a DevOps approach. In this way, operational data could be used to improve the process and make adjustments on the fly.

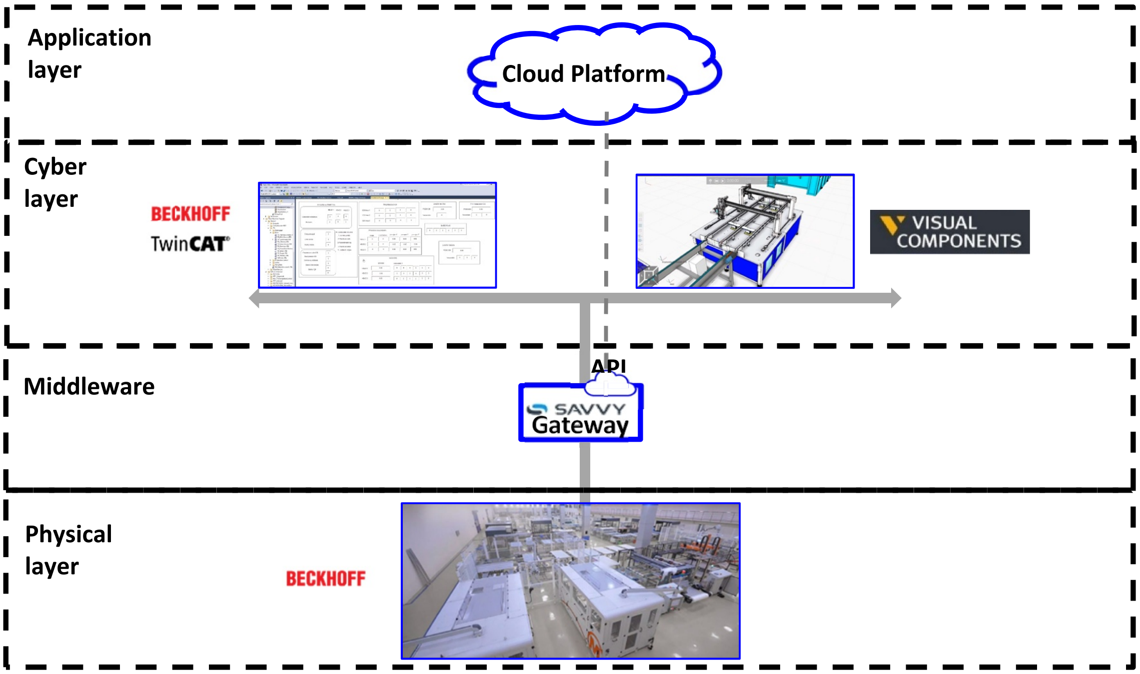

FIGURE 8 Mondragon Assembly holistic solution architecture

Design Prototyping & Virtual Commissioning

Mechanic	- Testing electrical axes - Checking synchronisation between raising and centering supports - Checking synchronisation between gantries
Electronic	- Validation of communication signals - Validation of electronic CAMs
Automation	- Validation of control logic changes - Validation of control sequences
Process	- Optimisation of control sequences to reduce cycle time - Simulation of sequence times

FIGURE 9 Collaborative virtual commissioning

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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