Transforming Brownfield Factories: Unleashing the Potential with Co-Engineering and Virtual Commissioning

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***Abstract*—Manufacturing lines are subject to continual change as components inevitably wear down over time, necessitating replacement. Often, the exact original parts may no longer be readily available, or an upgrade to integrate new technology becomes desirable. The crux of these scenarios lies in swiftly and seamlessly incorporating these changes, minimizing disruption to the existing processes. To address this, we put forward a concept utilizing a digital twin, complemented by an open-source industrial IoT framework. This combination facilitates both software and hardware loop integration, paving the way for efficient co-engineering development with existing legacy systems. Through this approach, we enable swift technological integration, keeping the manufacturing process agile and up-to-date.**

***Index Terms*—Industry 4.0, Digital Twin, Cyber-Physical Systems, Brownfield Manufacturing**

I. Introduction

Computer-Aided Design (CAD) is a standard industrial tool for designing mechanical and electronic products. The combination of different CAD tools has resulted in the concept of co-engineering; that is, development phases that were previously sequential can now be performed in parallel or simultaneously. This approach saves time and resources, reduces cost, and allows a business to remain competitive and integrate new technologies rapidly.

A most impressive accomplishment of co-engineering is the development of a car. What used to be a development cycle of six years for a new car has, with co-engineering, become a mere eighteen months process [1]. The engineering phases of the development cycle operate together, exchanging information as the product design advances. To find the optimal product, hardware and software must be developed and simulated together. The hardware-in-the-loop (HIL) and software-in-the-loop (SIL) concepts are used to set up and test drive-train solutions before they are even built. Manufacturers had to adopt these methods in the car industry to remain competitive. While the accomplishment is noteworthy, it is essential to note that it may only apply to new production systems and factories. The challenge is integrating these modern systems into the preexisting legacy systems.

Today's industry relies on currently existing technology - legacy systems. Using a factory's legacy systems in combination with new technology is more resource efficient than building an entirely new factory. This is because of the ever-changing manufacturing and development methods that the industry constantly adopts. These factories are called brownfield factories and can, in terms of development, be compared to a car's development cycle. While greenfield factories have great tools for co-engineering, brownfield factories do not.

Consider an old factory where one of the manufacturing cells requires a replacement. The existing production line infrastructure relies on Modbus for communication medium, and the management wants to convert gradually to using OPC UA. Can we decrease the development time and resource requirements for this evolution using co-engineering? In this paper, we approach the need for greater system interoperability by merging simulation, visualization, and validation tools with a service-oriented architecture (SOA) in the age of Industry 4.0. We create a digital replica of a model factory created by fischertechnik; it acts as a digital twin to its physical counterpart. The digital twin is operated using the same PLC software as the physical twin and is just as integrated with the rest of the systems by exposing its capabilities as services.

The remainder of the article is as follows. Section II provides some background on essential concepts. Section III describes and illustrates the proposed approach. Section IV presents a proof of concept. Section V discusses the proposed concept. Lastly, Section VI concludes the work.

II. Key Concepts

CAD is by no means a new concept for developing manufacturing methods. Despite being common practice, little to no effort has been made to incorporate its full potential into brownfield factories. Being able to retrofit fully digital systems with legacy systems contains significant benefits to the industry that will save extensive amounts of time and resources alike.

Siemens software Process Simulate is a tool used to enable enhanced co-engineering. It is designed to help manufacturers reach the market faster by allowing a virtual confirmation of the manufacturing line before going to production [2]. Albeit having the benefits of a digital test bed, Process Simulate is heavily aimed at entirely new factories, omitting to address the simulation needs of retrofitted developments.

Today, digital twins are used in various development and monitoring applications. Whether for a production line visualization or document-based data acquisition, the need for a digital twin is the same. The twins' interoperability defines a digital twin, not what shape it holds.

Kortelainen et al. did, in April 2023, a review of current developments of digital twins. In one case, they described using a digital twin in a manufacturing system using previously done research. The case emphasizes how digital twins integrate with different domains but do not clarify how the integration is created [3]. Another interesting case that the paper reviews is that of a manufacturing process. In this study, the authors stated that the previous work had been centered on providing means for enhanced communication and data usage [3]. It concludes a previous work by stating that using digital twins does not end with development but can also provide feedback on product usage and the end of product life. The review presented by the authors mentioned several cases where digital twins are at the center of development, yet, the need for backward compatibility and system integration is rarely mentioned. As long as interoperability between systems remains disclosed, the wish for the true potential remains just that, a wish.

Creating system interoperability is a challenging task. A manufacturing facility uses many different systems, and there is no guarantee that the systems use the same tools for communication. Toc et al. described system interoperability challenges between two standard protocols of industrial applications, namely the OPC UA and the Modbus protocols. These are two widely used protocols in industrial applications, yet, the solutions currently available are application specific. The paper provides an approach with hardware-based middleware placed locally to connect the physical environment to the digital [4]. Despite being a success, the solution is catered to quickly deploy local solutions strictly for Modbus to OPC UA conversion. It shows that interoperability is not easily achieved, and there are still gaps regarding facilities where the systems are yet to be acquired. Suppose a manufacturer does not have the physical systems and does not know what protocol the physical system will use. Simulating and developing the new systems is a significant challenge in that case. In this paper, we propose an approach that, with a framework, enhances possibilities for system interoperability to ensure a protocol-agnostic solution.

III. Indistinguishable Twins

We propose and illustrate the concept of indistinguishable digital twins that further improve interoperability with the remaining legacy application systems. The indistinguishable twins consist of a physical twin and a digital twin identical to the external systems. In industrial manufacturing, many different systems communicate with each other to create a production chain. This challenges the digital twin since it often relies on available data rather than system communication. The indistinguishable twins address the issue by being able to interact with real-time systems. Whether the real-time system is communicating with the physical or digital twin, there will not be any difference.

A. Integration with the Eclipse Arrowhead Framework

The Eclipse Arrowhead framework is an open-source, micro-service-based architecture created to further automation. Eclipse Arrowhead framework offers a local cloud-based approach to provide systems with security, interoperability, and real-time communication. Each local cloud includes core systems, such as the Service Registry, Orchestration, and Authorization systems [5].

The indistinguishable twins use the same PLC software to operate. Controlling the physical twin is a Siemens PLC capable of acting as an OPC UA server. OPC UA offers the server's data as a node with an ID and corresponding data. The nodes are scanned to integrate the twin's application system into the framework, and the IDs are copied to the name of the services. The Eclipse Arrowhead framework offers service information in the JSON format, commonly known for many protocols. Since the twins use identical application systems, they use the same OPC UA client system to offer the services.

B. Interoperability of the Twins

Using identical application systems, the twins can register their services to the framework using the same software. The OPC UA server holds sensitive information, but with the frameworks Authorization system, only the allowed systems can access the services. This is one advantage of the Eclipse Arrowhead framework that not all frameworks offer. Having the twins offer their details as services, such as position, activity, and sensor or actuator status, the other twin can access and respond to this information. It creates interoperability where one twin can affect the other twin's action or vice versa.

C. Integrating External Systems

Offering position and other signals as services, such as sensors and actuators, does not only benefit the communication between the twins. Since the local cloud-based framework can handle requests as well as orchestrate responses, with the use of the Orchestration system, external systems are also able to access these services.

Consider a manufacturing line; a conveyor belt can request a sensor to ask if it can read an object standing on the conveyor belt and start if it does. If the current manufacturing line consisted of legacy systems, it would be challenging to simulate and evaluate whether a new system would fit into the process line. Taking advantage of indistinguishable twins, it is possible to design the new system, simulate it with direct inputs from the conveyor belt and then evaluate whether the system in question would work. Figure 1 illustrates the legacy systems possibility to communicate with both twins.

It is a significant benefit to co-engineering in brownfield factories where new systems constantly need interoperability with legacy systems. The ability to fully develop the new systems before the physical hardware is in place allows the engineers to perform extensive tests and have the software ready to go once the physical application is in place.

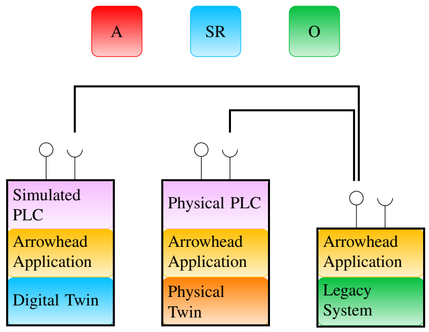

Fig. 1: Illustration of the interoperability concept. The legacy system offers its details to both indistinguishable twins.

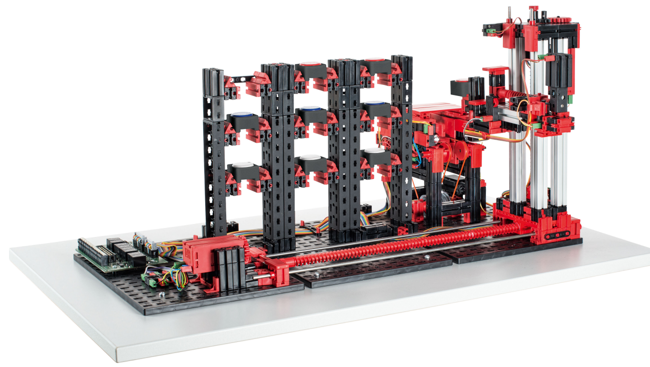

Fig. 3: The HBW station, made by fischertechnik [6].

IV. Proof of Concept

A model factory produced by fischertechnik is used in this paper to act as a manufacturing facility. It is controlled by PLCs, standard hardware used in current industrial applications.

A. The fischertechnik Factory

The physical twin created in this paper consists of a model factory, illustrated in Figure 2, a Siemens PLC, and its Arrowhead-compliant application system. The model factory contains four different stations, the High-Bay Warehouse (HBW), Sorting Line (SL), Vacuum Gripper Robot (VGR), and the Multi-Process Station (MPS) [6].

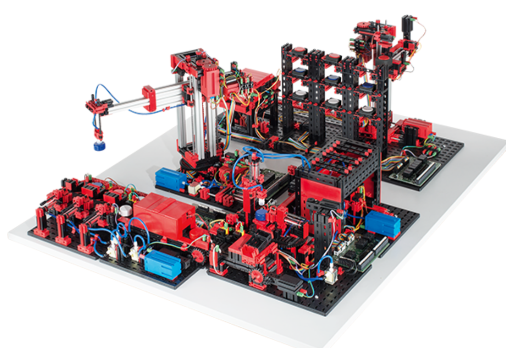

Fig. 2: A physical model factory, made by fischertechnik [6].

For this paper, the experiment is focused on one of the stations, the HBW. The HBW consists of three main components: a short conveyor belt, a horizontal and vertical positioning lift, and a warehouse shelf. The HBW is illustrated in Figure 3. The station is connected to a PLC with the logic to operate it. Developing code and uploading it to the PLC software is needed. The PLC used in this experiment is a Siemens SIMATIC ET 200SP. Hence Siemens software, TIA Portal, is used to program and upload code to the PLC. The code for the entire model factory is available at fischertechnik's GitHub[1]. The code created by fischertechnik is designed to control the factory in its entirety and has therefore been altered to fit the needs of this experiment. The code related to the HBW and signals bridging the different stations has been kept and altered to be independent of the remaining stations. By making the physical system interoperable like this, it can act alone and use the digital twins remaining stations. It represents a factory's possibility to test a new system concept before implementing it with legacy systems.

[1] https://github.com/fischertechnik

B. The Digital Twin

The visual model is created using Siemens's software NX. The physical model factory was disassembled to acquire the correct measurements of the building blocks. The core building blocks are modeled using the modeling application. The complete model factory presented in Figure 4 is assembled using the assembly application.

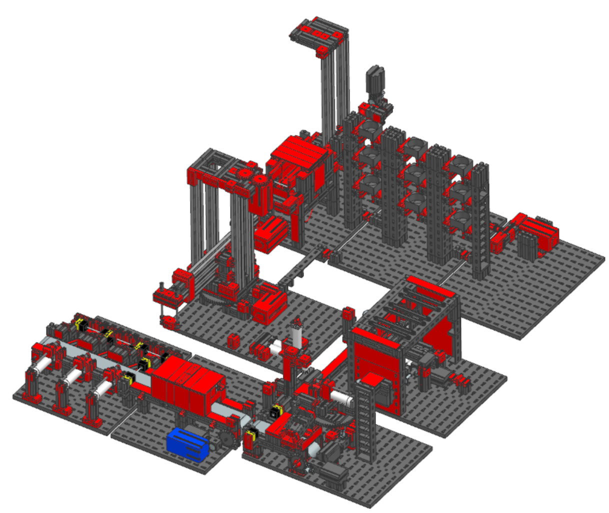

Fig. 4: Illustration of the full assembly of the digital model factory.

Having created the CAD assembly of the model factory, we adopted the behavior of the real system with the application Mechatronics Concept Designer (MCD). The MCD application allows the digital model to receive external signals to the simulation and use them to control the digital model factory.

The electrical motors that control the physical factory are pulse motors. Simulating these pulses in NX MCD is challenging and vital for the digital twin to operate as an indistinguishable twin.

The digital twin is simulated using velocity, position, and time. By creating variables that take the position traveled and converting it to pulses, NX can send data to the PLC matching that of the electric motors. The motors send signals using two encoders, and with different offsets in the output, they can change the direction of the movement. Equation 1 and 2 describe the encoders in the simulation. r_e is the resolution of the encoders, r_a is the angular resolution of the motors, R is the rotational factor, and $A1$ respectively $A2$ are the encoder values.

$$A1 = -\text{sign}\left(\frac{180}{r_e} - \left(\frac{270}{r_e} + \frac{R}{1}\ mod\ 360\right)\ mod\ r_a\right) = \begin{cases} \text{true}, & \text{if } A1 > 0 \\ \text{false}, & \text{else} \end{cases} \tag{1}$$

$$A2 = -\text{sign}\left(\frac{180}{r_e} - \frac{R}{1}\ mod\ 360\ mod\ r_a\right) = \begin{cases} \text{true}, & \text{if } A2 > 0 \\ \text{false}, & \text{else} \end{cases} \tag{2}$$

Since the electrical motors only give one pulse at a time, we want the simulated encoders to give the result 1 or 0. If the result is *true* a counter will increase its value by 1. It will represent the physical twin's step counter and result in the digital twin adopting the physical twin's exact behavior.

The digital model contains all crucial parts of the physical twin factory with minor deviations. Simulating a visual digital twin with a complex geometric representation is demanding; hence, some simplifications are necessary. The level of detail varies from one application to the other. In this use case, the physical twin is a more straightforward conveyor belt, which reduces the need for detail.

Creating a relationship with the physical model factory is crucial to establish the digital model as an indistinguishable twin. The relationship between the twins is illustrated in Figure 5. As the illustration implies, both the twins are programmed with TIA Portal and operated with the logic of a PLC.

When creating the digital twin, it is essential to consider properties such as speed and positioning of objects. The DC motors controlling the factory have a fixed speed which must be matched in the digital twin. If not, the TIA Portal code can be identical but give different outputs.

C. Indistinguishable Twins

The next step is to integrate the twins to ensure system interoperability and that the twins are identical. In doing this, we show that the twins can operate using the same software and application systems and that interoperability works as intended.

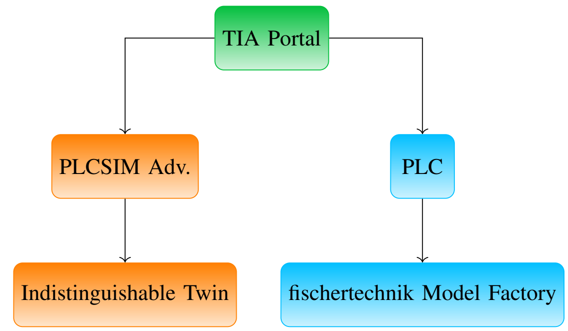

Fig. 5: Illustration of the relationships between the hardware and software.

A client system extracts the nodes from each system, registering the node ID as the service name to the Service Registry system of the local cloud. A consumer requests the core systems, asking for a specific service; this process is illustrated in Figure 6.

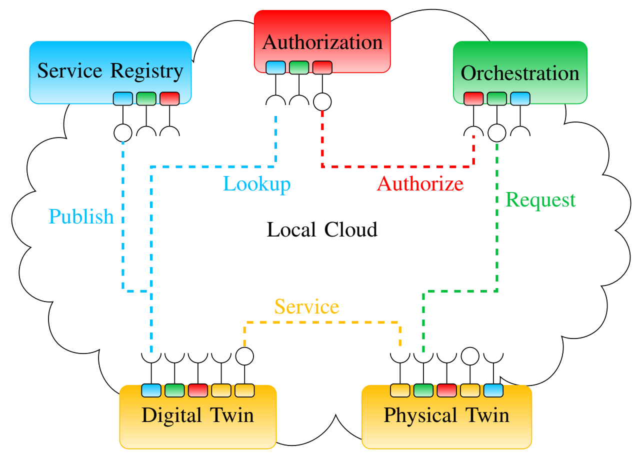

Fig. 6: Illustration of a local cloud, its core systems, and the application systems used in the research [7].

As the illustration shows, the Digital Twin system publishes its services, and the Physical Twin sends a request to the Orchestration system. The core systems create a transaction that causes the physical twin to consume a service from the digital twin. The result is a seamless interaction between the twins where the Arrowhead framework provides a commonly available protocol.

V. Discussion

The use-case provided in Section IV illustrates that incorporating the Arrowhead framework has significant benefits regarding system interoperability. Enhancing the system interoperability and having a digital twin identical to the physical twin creates an environment where systems can be fully developed before the physical hardware is installed. It distances itself from the current static nature of digital twins by merging with the Arrowhead framework to operate using data from the physical systems at hand.

An initial challenge with implementing the indistinguishable twins was making them act identically. Going into this research, it was unclear exactly how the physical model factory operated and how the TIA Portal code was structured.

Despite the achievements, there are challenges in the proposed approach that needs to be addressed. The lack of real-time simulation needs improvements in future developments of the proposed concept. The current implementation would not be able to rely on real-time interaction to visualize what the factory is doing. Improving these capabilities will benefit monitoring and be a significant benefit for mobile control of the factory.

The current Go implementation of the Eclipse Arrowhead framework is yet to be fully developed. Its complex implementation holds the risk of being too difficult for industrial application. To fully take advantage of the benefits that indistinguishable twins can offer, the time it takes to install new systems must also be reduced.

VI. Conclusion

We propose a concept to enhance the abilities of digital twins through system interoperability, a crucial element in advancing brownfield manufacturing facilities. Indistinguishable twins merge simulation, visualization, and validation tools with an SOA, aiming toward Industry 4.0. This approach bridges a crucial gap, facilitating concurrent engineering when developing manufacturing lines incorporating legacy systems.

Indistinguishable twins have proven to be beneficial to apply to the industrial workspace. The current development cycle process is often too time-consuming and resource-heavy to go through constantly. Applying the proposed concept, developers can concurrently develop and test new manufacturing concepts as the current implementation runs. It is an achievement that has the potential to save manufacturers a significant amount of time when applying a new system in a brownfield factory.

Current solutions are more aimed at entirely new systems or facilities where the entire production line is simulated to find optimal solutions. Co-engineering has an inherent place in these developments and is also part of why the development cycle time for greenfield factories has been reduced. Structuring an entirely new production line is free from having to keep legacy systems in mind since it is an open space waiting for the physical systems to be implemented. On the other hand, brownfield factories rely on legacy systems and must ensure interoperability between what is new and old. Despite all the advancements made regarding manufacturing development, brownfield factories tend to be behind. Often requiring sequential engineering to test and adapt the new process before implementing it. The proposed solution enables co-engineering for the brownfield factories where digital twins fail.

Future work related to indistinguishable twins includes the simulation time scale. The current implementation of the proposed approach requires heavy computational power and is a challenge for the hardware to handle. Continuing the work, the following work should address the need for real-time simulation, which would benefit the indistinguishable twins' monitoring and mobile control capabilities. As we advance with the research, it is essential to implement more protocols to establish global compatibility. The work related to this paper is done with the OPC UA protocol. The most important aspect of interoperability in brownfield factories is yet to be implemented. Moving forward, it is essential to implement and test Modbus and other major protocols often used in PLCs. Future work will include the introduction of a Modbus PLC to a station in direct relation to the HBW. It will put pressure on the error tolerance of the communication, and the mobility of adding and removing systems can be tested to a greater extent.

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