White Paper

Digital Twin: Production of Tomorrow — The "Not-Your-Average-Paper"

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Abstract

Imagine a future where production systems are not just efficient but intelligent, where machines, products, and entire factories communicate seamlessly, adapt in real time, and operate autonomously. This white paper introduces a vision for that future, centered around the concept of digital twins. As industries transition away from rigid, outdated systems, the potential for digital twins to revolutionize production is enormous. They open up possibilities to transform today's fragmented production systems into fully interconnected, self-optimizing environments. Additionally, we explore how these digital twins can reduce the burden of repetitive tasks, freeing human talent to focus on innovation, problem-solving, and strategic growth.

To make this vision more tangible, we've structured the evolution of digital twins into six distinct phases, each representing a key step in their development - from basic data collection to full autonomy. Much like the journey of growing up, these phases highlight how digital twins mature and gain capabilities, ultimately transforming the world of tomorrow.

Join us as we break down these six phases, showing how digital twins gradually evolve into fully autonomous systems. With each phase, you'll see the future of production take shape and where intelligent, interconnected systems redefine what's possible in manufacturing, pushing the boundaries of efficiency, adaptability, and innovation.

Table of Content

1 Introduction

Global production is undergoing a significant shift, as industries move away from the stable, optimized systems of the past and adapt to new, evolving conditions. The growing recognition of the value of data emphasizes the need to rethink and modernize production processes. Now is the time to address the future of manufacturing, identifying both the gaps in today's systems and the necessary steps to remain competitive.

Current technological solutions, though advanced, are often fragmented and lack the ability to operate seamlessly across systems. For instance, robots with camera systems can now navigate complex environments and optimize their actions, but they are still limited by their inability to interact independently with other systems or provide real-time feedback. These constraints require ongoing human intervention, which slows down operations, increases error rates, and reduces overall efficiency. The human factor in production is far too valuable to be burdened with repetitive setup processes, which should be handled by autonomous systems.

In this White Paper, we present a vision for the production of tomorrow. We focus on the concept of digital twins which can be described as comprehensive digital representations of products, machines, and systems. Digital twins can provide a solution to many of the challenges faced by modern manufacturing by enabling greater interaction, autonomy, and seamless collaboration across systems, creating the foundation for a more flexible, efficient, and interconnected production environment.

2 Before We Dive In – Let's Clear Up a Few Terms First

In this chapter, we aim to clear up a few important terms that will be referenced throughout the document. We will be discussing the digital data container, the digital twin, and the autonomous avatar - three key terms that are crucial for understanding the overall story and idea presented here. First, we'll introduce the digital data container, which functions as a structured repository for information. Next, we'll explore how it becomes a digital twin once it gains the ability to interact and collaborate. Finally, we'll explain the concept of the autonomous avatar, a more advanced form of the digital twin that can act autonomously. These terms will play a central role in the sections that follow, so it's important to get a clear understanding of each.

2.1 The Digital Data Container

The digital data container is a comprehensive, standardized repository that collects and stores all relevant information across a product's lifecycle. A product is not something that necessarily has to be the "to be produced object"- it can also be a workpiece or tool. It serves as a single source of truth, where data from various systems - such as ERP, MES, and CAD/CAM - are centralized. Accessible via a unique ID, the container holds critical data for production assets and the product itself, providing a unified, flexible space for both storing and sharing information. However, the container itself doesn't perform any actions or interact with other systems - it merely stores and organizes the data. Now, what makes the container really viable?

To summarize: the digital data container stores information.

2.2 The Digital Twin

The concept of the digital twin is one of the most prominent buzzwords in the context of Industry 4.0. While the idea of a digital twin is frequently discussed in industrial settings, it is often understood in different ways. These divergent interpretations have led to a variety of digital approaches, many of which don't scale well - and that's a problem. As a result, standardized digital twins are becoming increasingly important as the hub for seamless information flow in industrial production processes.

In the context of the "production of tomorrow," we define the digital twin more broadly. We see it as a comprehensive, lifecycle-spanning, standardized digital data container that, when needed, can interact with the containers of other physical counterparts within reasonable limits. A digital data container "evolves" into a digital twin once it gains the ability to interact and collaborate, elevating it beyond a simple storage tool. This ability to interact is a crucial factor in making highly autonomous production a reality.

To summarize: the term digital twin is used when the digital data container interacts and collaborates.

2.3 The Autonomous Avatar

The concept of an interoperable digital twin is not entirely new. In the IT world, a similar function is referred to as an "autonomous agent." An autonomous agent not only reacts to its environment but also actively influences it in order to achieve its predefined goals. However, in IT, this term typically brings to mind highly specialized software programs designed for narrowly defined use cases. There are also comparable concepts, such as the "proactive administration shell" (introduced by the IDTA - Industrial Digital Twin Association e.V.) or similar approaches, which attempt to capture this idea of interaction and autonomy.

We could treat terms like interoperable digital twin, proactive administration shell, and autonomous agent as equivalent, assuming they all refer to the same concept. However, this would likely lead to a semantic debate that diverts attention from the core idea. To not get hung up on this, we propose the concept of the "autonomous avatar". An avatar, in its common definition, is a digital representation acting as a proxy. In the context of production, this term conveys a broader vision, combining autonomous interaction, standardized information modeling, and - most importantly - breaks away from the traditional thinking patterns.

To summarize: an autonomous avatar is a digital twin that acts autonomously.

3 6 Phases of Growing Up: The Path to Autonomous Avatars in the Production of Tomorrow

To make the concepts more accessible and bring a bit of lightness to the topic, we'll use the analogy of growing up. Just as a child learns foundational skills before becoming fully independent, the development of autonomous avatars in the production environment follows a similar path. In the upcoming sections, we'll explain how these avatars start by learning the basics, like gathering and storing information, before taking their first steps in interacting with other systems, and finally evolving to make independent decisions and drive processes autonomously. Throughout this journey, our focus remains on boosting efficiency, flexibility, and resilience in the "production of tomorrow".

3.1 Phase 1: The Childhood of a Digital Data Container

In the first phase, we introduce the digital data container, which, like a child in its early years, is in the process of learning. During this stage, data containers are created for all key production resources, such as robots, process tools, or conveyor belts, and filled with all relevant information. Even the product itself receives its own data container, which grows over its lifecycle, gathering and storing essential details. At this stage, all information is now centrally located, forming a single source of truth, accessible through a unique ID by both humans and systems. However, like a child still learning the basics, the container doesn't yet interact with other systems or make decisions on its own - it simply stores what it has been filled with. These containers, at this stage, function much like traditional file links, which can be shared with systems, business partners, or other stakeholders. Depending on the role and responsibility of the user, the container serves as both a data source and a system-independent storage location for new information. In essence, it acts like a young child collecting knowledge from various sources – parents, nature, friends and… white papers of course.

The flexibility of these containers is also key. These containers can be stored in flexible locations, either hybrid or decentralized. They passively gather and organize information, helping to ensure everything needed for production is in one place. In other words, during this initial phase, the data related to the workpiece and its production flows from various existing company systems into the data container. The goal is to gather and provide all digitally available information for the workpiece to be processed. For example:

- order data from an ERP system
- planning and execution data from an MES system
- design and manufacturing data from CAD/CAM and PDM/PLM systems

This data is either referenced or copied into the workpiece's container and subsequently unified. The container holds, for instance, the production plan, the program name for the next machine operation, the assembly instructions for upcoming tasks, and much more. Throughout the entire lifecycle of a workpiece, extending far beyond the actual production process, this passive, system-independent container proves to be valuable. It can be used for tracing, such as providing feedback on completed work, or for other essential records, like verifying maintenance intervals or tracking the product carbon footprint (PCF).

Let’s not just focus on the boundaries of the product itself. To truly achieve autonomy, we need to consider all aspects of production. Every part of the process plays a crucial role. Alongside the product (which is created when a workpiece is processed), tools also receive their own digital data containers as described above. The container for a tool holds essential information such as usage guidelines, technical requirements like power and voltage specifications, machine compatibility, and the necessary employee training required to operate the tool. Similarly, machines also have their own containers for their digital models. These containers reflect important details such as the machine’s processing capabilities, its current operational state, and the tolerances it can handle. Just as every component in a production line must work in sync, these data containers ensure that every tool and machine is digitally integrated, supporting the gradual shift toward autonomy.

3.2 Phase 2: Applying What’s Learned – The Digital Twin

In Phase 2, we move beyond simple data storage. Just as a young adult begins applying what they’ve learned, the digital twin now steps up, actively interacting and executing tasks. However, these actions are still based on prior experience and predefined rules. The twin hasn’t yet reached full autonomy but is using established knowledge to make decisions and perform tasks. Building on the centralized data from Phase 1, the foundation for tomorrow's production is further solidified in Phase 2. We no longer deal with passive information containers that function like file links. For software systems to allow the product, tool, and machine containers to "communicate" with each other, it's crucial that the data is structured and described in a semantically clear way.

In other words, all data must follow the same "dictionary," ensuring that everyone speaks the same language.

At this stage, the previous container “evolves” into a standardized digital twin because all information now follows a unified semantic framework. A central logic orchestrates these interactions, initiating and enabling the communication between the standardized digital twins and guiding the production process. For example, the system queries the digital twin of the product for the next production step and its associated program, processes that information, and then directs it to the appropriate machine, providing its operation with the necessary instructions. While the digital twin is now capable of interaction, decision-making, and execution, much like a young adult using the knowledge they’ve gained, its actions are still rooted in predefined guidelines rather than independent decision-making. This phase marks a significant leap forward, yet true autonomy lies ahead.

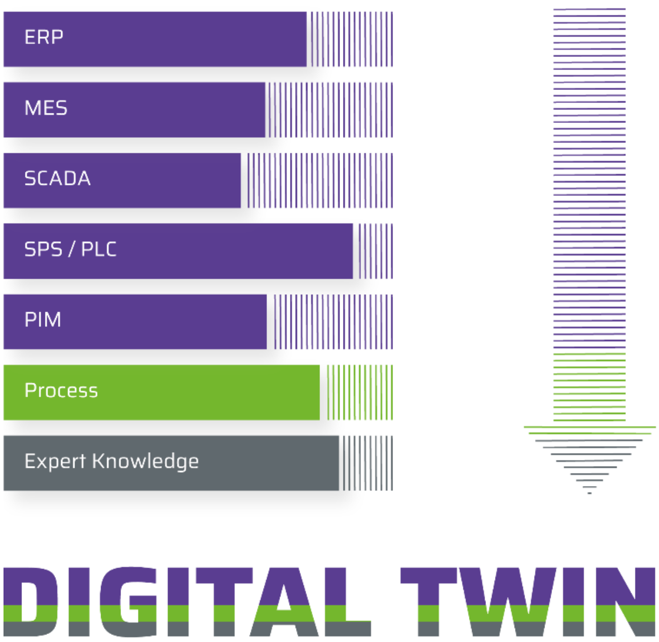
3.3 Phase 3: Stepping into Adulthood – The Autonomous Avatar Takes Charge

After establishing standardized digital twins that were previously controlled by an overarching logic, some of that control now shifts into the product's own digital twin. This means that functionalities traditionally handled by systems like MES and SCADA, such as machine parameters and set values, gradually become the responsibility of the product's increasingly interoperable digital twin. This shift allows the twin to make autonomous decisions, such as selecting from alternative production sequences or choosing between available machines based on the work plan and its defined degrees of freedom. Thus said, in Phase 3, the digital twin evolves into an autonomous avatar, much like an adult who has matured beyond simply applying learned knowledge. Now, it begins to make independent decisions, using its own logic and reasoning capabilities. No longer just following pre-defined instructions, the avatar is able to analyze and infer new insights, applying a deeper understanding to navigate its environment.

At this stage, the product’s avatar, according to its workflow plan, can autonomously determine which machines or processes to engage with next. If there are alternative paths or machines available for processing, the avatar evaluates its options within its given parameters and selects the optimal route. However, human input, such as insights from production planners, remains crucial. These human-provided experiences and knowledge fuel the avatar's ability to make autonomous decisions, much like an adult who draws on both learned skills and external advice. The transformation from digital twin to autonomous avatar now incorporates:

- Semantically structured data, clearly described for precise interpretation.
- A rule engine, capable of processing rules and making decisions.
- A workflow engine, which manages and executes process chains.
- The ability to communicate with different machine protocols and send configuration parameters directly to machine controls when needed.

The autonomous avatar continuously updates its knowledge as production progresses. Completed processing steps are marked as finished within the avatar and paired with relevant data, such as measurements or results. Some of the logic and content thus shift from the systems to digital twin – or in this case, as it is making autonomous decisions – the avatar. The unique advantage now is its ability to make decisions at the point of production, based on decision criteria, including all rules and underlying foundations.



This ensures the product knows which step is next, and the avatar gains the ability to recognize and even modify its own status. At this point, the avatar carries all relevant information within itself. Previously, gathering this data from various complex systems was a challenging task, often requiring significant effort. Information was typically scattered or buried deep within specific systems, and only human operators knew where to find it. The autonomous avatar now eliminates this complexity by holding all the necessary data in a structured and accessible way. This shift significantly reduces the manual effort involved in locating crucial production information **– the avatar ensures that human efforts are focused where they truly matter.**

3.4 Phase 4: Collaborating in Adulthood – Autonomous Avatars Working Together

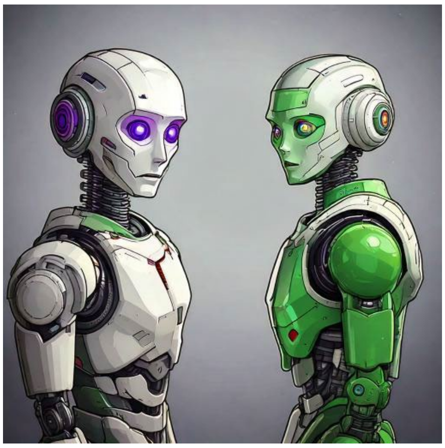
In Phase 4, the autonomous avatar, now much like an adult, has reached the stage where it collaborates with others to accomplish tasks. No longer working in isolation, it interacts seamlessly with other autonomous avatars in the production environment, coordinating efforts and adjusting plans based on real-time information. This stage represents the autonomous avatar's growing independence and ability to make decisions in cooperation with others. To move to the next production step, the autonomous avatar must now communicate with the logistics system to handle transport requests.

In this phase, the autonomous avatar is capable of responding to logistics events and can adjust its internal plans through a built-in rule system. For instance, if no automated transport vehicle is available, an alert can trigger a human-assisted transport instead. Even before the transport process is completed, the product and machine autonomous avatars can exchange their needs (e.g., configuration parameters) through interfaces. This allows the machine to prepare in advance, adjust its setup, and load the appropriate program - it essentially configures itself. As a result, fewer process experts are required on the production floor, since the autonomous avatars handle much of the preparation work autonomously.

The autonomous avatars also check for compatibility: the product's avatar communicates with the gripper's avatar of a production robot to confirm its readiness. This gripper's avatar, in turn, consults the tool changer's avatar to verify if and when they can work together within the designated workspace, then provides feedback. The autonomous avatars' internal information regarding their capabilities allows them to determine the optimal approach for the task at hand.

In this phase, all autonomous avatars communicate with each other to ensure the best possible production outcome. Flexible production approaches that require frequent re-planning are now supported by the standardized self-description. The system automatically identifies the "perfect match" between the product's requirements and the machines' and tools' capabilities, even enabling the automatic selection of the appropriate manufacturing process. While the avatars manage much of the decision-making autonomously, an overarching planning system still handles higher-level decisions or conflicts between these avatars. However, the complexity of future planning systems is reduced thanks to the avatars' ability to make ad hoc decisions at the point of production. Depending on availability, alternative machines or resources can be automatically selected and integrated into the workflow, allowing for dynamic and efficient production processes.

3.5 Phase 5: Facing Challenges – Autonomous Avatars in Competition



In Phase 5, the autonomous avatars encounter real-world challenges, much like adults navigating conflicts and problem-solving in life. Collaboration doesn't always go smoothly, and sometimes competition arises. The avatars, much like humans, need to manage and resolve conflicts to maintain efficiency. In this phase, an autonomous avatar never operates in isolation - there is competition. Multiple autonomous avatars may simultaneously need access to a bottleneck resource, such as a machine. The autonomous avatars now possess the ability to handle these competitive situations, negotiating and managing the order in which tasks are performed.

When multiple products require the same machine at the same time, or when an urgent order arises, the processing sequence is dynamically determined. Configurable parameters for each autonomous avatar, set according to the situation, help guide the decision-making process, which is overseen by a higher-level planning intelligence. If, for example, there is a disruption with the highest-priority product, lightweight future planning systems will reassess the situation in real time. They will evaluate the urgency of all competing products based on the current needs of their autonomous avatars and adjust priorities accordingly. The autonomous avatars are then updated, allowing for quicker processing and more responsive production flows.

As with humans, who learn from experience, these autonomous avatars are also equipped to learn from historical data and patterns. AI-driven intelligence constantly identifies opportunities for improvement and recognizes suboptimal production processes. Efficient operations are measured based on key factors, such as:

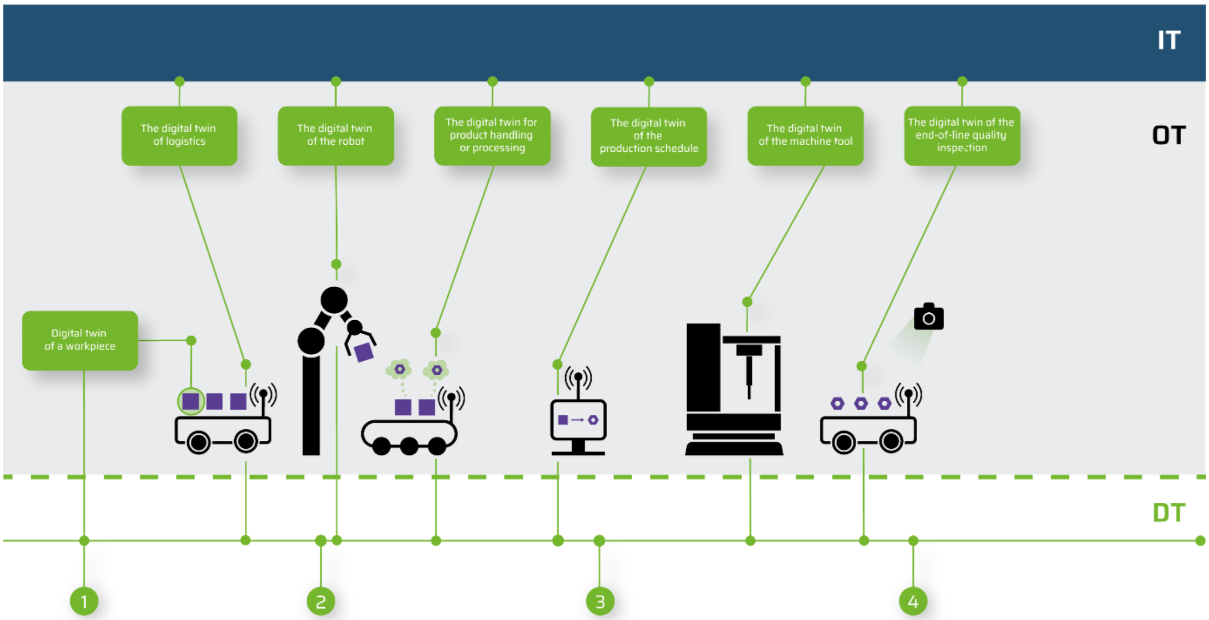
- speed and quality of product manufacturing
- optimized machine utilization
- ensure, that tools are maintained and available just in time

The autonomous avatars, driven by this intelligence, can optimize their decisions within their predefined limits. They can also predict and prepare for potential issues, such as equipment defects, helping to prevent downtime and inefficiencies.

3.6 Phase 6: Expanding Networks – Autonomous Avatars Beyond Boundaries

In Phase 6, the autonomous avatars step into a new level of interaction, much like adults who expand their social and professional networks beyond their existing circles. In this phase, autonomous avatars are no longer confined to operating within a single company - they begin to collaborate across organizational boundaries, interacting with avatars from other companies, such as suppliers and customers.

At this stage, the autonomous avatars and their associated data containers are passed from suppliers to the manufacturing company, where they continue to be enriched with additional information. This seamless transfer of data across company borders opens up entirely new possibilities, contributing to enhanced product tracking and quality optimization. By sharing information beyond the company's walls, feedback from customers down the production chain can be sent back to the original suppliers, enabling continuous improvement. Additionally, this phase provides transparency to customers, as product users can access relevant information about the product whenever they need it.



1 Fundamentals

- Relieves workload from MES, ERP, and SCADA systems
- Records all essential information and makes it available
- Serves as the extended arm of future AI
- Enables autonomous communication between individual digital twins (e.g., AGV, robots, machine tools)

2 Work preparation

- Knows its own work plan, parameters, and requirements for each task
- Can respond to events based on its rules and independently choose between options
- Can verify with the machine if its capabilities align with the digital twin's requirements

3 Production

- Can initiate communication with machines and tools
- Provides the planning system with the latest boundary conditions for itself
- Self-classifies, e.g., as second choice if measurements aren't optimal
- Can request new decisions from the planning system

4 Cross-company

- Can be transferred to a partner company
- Remains available even after the product has been delivered
- Serves as the foundation of the Digital Product Passport (DPP)
- Maintains the link to the production order
- Acts as the best source for after service and aftersales

Conclusion: The Path Forward

As we conclude, our message is clear: decisive steps toward innovation are essential. We encourage leaders to seize this unique opportunity and move confidently into the future. For those already well-versed in digital transformation, some of the concepts may feel familiar. However, the scale and significance of the changes ahead call for new approaches and a renewed commitment to progress.

Throughout the writing process, we, as the authors, gained valuable insights, and we are excited to announce that a second part of this White Paper will be released soon. In it, we will explore in greater detail why a paradigm shift is necessary, highlighting the urgency of maintaining competitiveness, and provide more in-depth technical insights and practical recommendations for companies navigating this transition.

Europe's industrial competitiveness and innovation strength hinge on its ability to swiftly and strategically adopt emerging technologies. To remain a leader in this evolving landscape, it is essential to implement bold, forward-thinking changes that reshape the foundations of industry. By embracing these shifts, Europe can secure its role as a major player in the global industrial arena, driving both growth and innovation. Europe has, in the past, hesitated during critical moments of digital transformation, missing key opportunities. Yet digital twins now offer a unique chance to not only recover lost ground but to shape the future of industry. These technologies enable smarter, more autonomous systems that can go beyond individual company boundaries, creating a resilient and flexible value chain.

We, as the OI4 Alliance, are not only committed to inspiring and supporting businesses on this journey but also, as an implementation alliance, to testing and refining practical approaches in collaboration with industry partners. Our mission is to ensure that companies have the tools and strategies needed to successfully adapt and thrive in this new environment. Europe's success in the next industrial era depends on its ability to swiftly embrace these innovations and work together to build a future of inter-company collaboration and automation. The OI4 Alliance is committed to this vision, and we invite other experts, thought leaders, and practitioners to join us in shaping this future. Together, we can ensure that Europe not only participates in but leads the next global industrial revolution. Let's make this vision a reality and position Europe as a trailblazer in the industries of tomorrow.