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Digital Twin Animation in Manufacturing: Identifying Gaps, Opportunities, and Implementing Solutions

Muhammad Amir Bin Mohamad Arif, Mohammed Malaibari and Shiva Abdoli
Senior lecturer, School of Mechanical and Manufacturing Engineering
University of New South Wales
Sydney, Australia
s.abdoli@unsw.edu.au

Abstract

Industry 4.0 revolutionized manufacturing, which digital twin is one of its key enabling technologies revolving around the idea of replicating a system's characteristics and behavior. Digital twin allows evaluating the impact of any decision or change on modern manufacturing system performance. However, there are still significant lacunae regarding digital twin animation in implementation: on real-time data synchronization, effectiveness in training, and integration within the system. This work conducts a thematic review and critically analyzed the available literature relating to digital twin applications within manufacturing and identified the following key challenge: communication barriers between the animated model and the physical system, high costs of implementation, and complexity in integrating animation with automation tools. This research provides practical insight into optimization of digital twin animation in view of overcoming some limitations and facilitating wider adoption in manufacturing.

Keywords
Digital Twin, Animation, Industry 4.0, Cyber Physical Systems

1. Introduction

Digital twin (DT) is defined as digital replica of an entity with connections allowing convergence between physical and digital states at an appropriate rate of synchronization and has gained attention for improving efficiency in manufacturing (Zhang and Zhu 2019, Abdoli and Ye 2023). Animation can convey system behavior graphically, useful in training, process optimization, and system monitoring, however high implementation cost and requirements of technical expertise to manage the cutting-edge technologies are barriers to its adoption (Khan et al. 2022, Vladimir Kuts et al. 2020).

The main objective of this paper is to identify potential opportunities for further innovation, and challenges that need to be addressed for more widespread adoption of DT animation in manufacturing with a critical analysis of existing literature and case studies. As part of the first phase of a larger project, this investigation provides a comprehensive understanding of technical aspects of DT animation in manufacturing. The contribution of this study to the field will be that readers will gain valuable insights into current state of research, practical applications, and potential for future advancements. Based on gaining insight through this critical review, the paper proposes strategies to overcome the identified challenges by leveraging the existing opportunities. By proposing strategies, this study aims at improving efficiency of DT animation in modern manufacturing systems. The methodology used to guide and structure the research which includes review, investigation and scoping is in Figure 1.

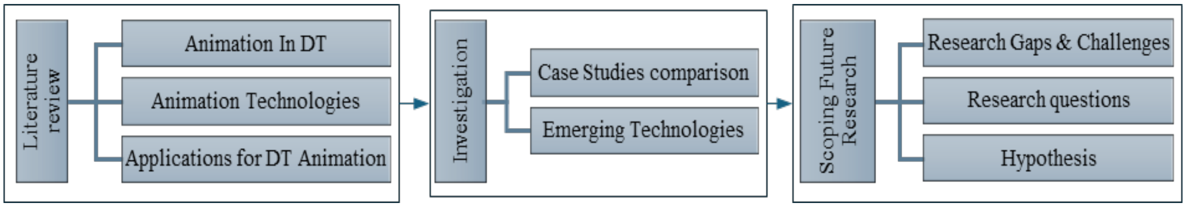


Figure 1. Research methodology

2. Animation In Digital Twin

DT in manufacturing has been used to monitor/optimize production systems (Kritzinger et al. 2018, Franceschi et al. 2021, Abdoli 2023), unifying data from various sources, such as sensors, Internet of Thins (IoT) devices. Animations in DT can make complex data or system behaviors more understandable and gives new perspectives, which is critical in applications such as process monitoring, operator training, design validation, and can support decision-making. DT animation of machine and material movement on a production line enable detection of possible problems (Eyre et al.2018). In training, animated models allow workers to interact with machinery, improving their understanding of the system without interrupting the process (Evangeline and Anandhakumar 2020, Abdoli and Djukic 2025). By critically reviewing literature, this paper defines DT animation dynamic, can be real-time, and visual representation of physical system behaviors. Unlike simulation, which relies on mathematics to analyze system behavior, animation emphasizes clarity to make complex systems more understandable from a user perspective (Zheng et al.2024, Tanberk et al.2024).

2.1 Types of Animation in Digital Twin Systems

Several types of animation can be applied with specific functions. The suggested six types in this paper were synthesized to represent the most frequently recurring animation categories in literature. It is worth clarifying that assembly systems are critical components of manufacturing; yet their animations involve process and system animations. To avoid overlapping, this paper introduced assembly systems as a separate category. Also, material handling may be viewed as a subset of logistics (Puniani and Abdoli 2025). This paper considered it as a separate category because logistics animation focuses on high-level system flows (e.g., supply chain transport), whereas material handling animation typically involves low-level, intra-facility movements (e.g., conveyors, robots). This allows for more precise categorization and analysis of animation strategies in DT applications. While simulation models system behavior using quantitative/algorithmic processes, animation refers specifically to visual representation of such behaviors. Although animations may use simulation data to visualize system dynamics to human users.

Product Animation: Behavior of a product is visualized mainly in design stage to show its performance. In industries such as automotive, product animations allow experimenting new designs virtually instead of physical prototyping (Zhang and Zhu 2019). Figure 2 shows 3-D material removing process animation of aeroengine Fan Blade Machining.

Fluid animation: this concept is used where liquid/gaseous interactions drive system operation to simulate behavior of fluids, pressure distribution and temperature influences in processes. Computational fluid dynamics (CFD) as a common method can be used to model cooling systems and lubrication mechanisms in injection molding processes, and liquid transport systems. Fluid animation during metal casting shows flow of liquid metal in a virtual environment. In hydraulic and pneumatic systems, CFD allows real-time pressure variation and leakage detection and enables programs of predictive maintenance. Common tools used in Fluid animation are: ANSYS Fluent, Open FOAM and Siemens Sim center STAR-CCM+, offering conduction of heat/turbulence models.

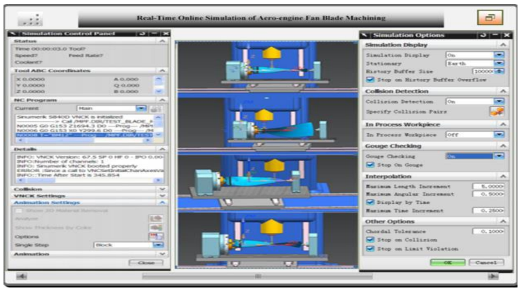
Process Animation: this imitates the flow of materials, information, and energy in a system, useful for visualization of logistics and bottlenecks in a line (Eyre et al.2018). Figure 3 shows the laboratory production line that has been animated for process monitoring.

Robot animation: this is used in testing robotic processes prior to installation, enables collision detection, identifying kinematic limits, and minimizing downtime during real-time operation. In industries including automobiles, electronics, and aeronautics, DT incorporate simulation of robots to estimate efficiency of assembling line, welding accuracy, and robotic arm coordination. An automatic robotic welding system can be modelled to calculate the best route planning prior to doing tasks in the line (Garg and Anbarjafari 2021)

System Animation: this approach models the complete systems, including machines, operators, and material flow, visualizing how different elements interact. System animation is important in monitoring and optimization of large industrial operations, factory floor management, where several machines/workers must be harmoniously coordinated (Eyre et al.2018, Kober et al.2024).

Logistic animation: visualizes the effects of various strategies on inventory levels, transportation efficiency, and throughput. A warehouse can utilize a DT to mimic the operation of autonomous-guided vehicles, routing patterns to optimize material flow processes and order fulfillment. Prominent software tools used in simulation of logistics include Any Logic, Simio, FlexSim, and Tecnomatix Plant Simulation, supporting agent-based modeling, discrete-event simulation, and system dynamics simulation (Barosan et al. 2020).

Material handling animation: visualizes flow of goods-in-process in a manufacturing system, playing a key role in optimization of handling processes and their elements such as conveyor belt system and robotic palletizing processes optimization. For example, at a distribution center, a DT animates the flow of goods from storage racks to packaging stations and help recognizing bottlenecks to enhance efficiency of order fulfillment process. Animation of forklift's automation allows testing the changing of conveyor belt speeds, and robotic pick-and-place technology in overall flow of factory. Commonly used tools that conduct animation of material handling include Simul8, Arena, AutoMod, and Siemens Tecnomatix Plant Simulation that optimize the logistics and real-time flow of the material during production (Tkaczyk et al.2023).



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Single Step: Block
Simulation Display: On
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History Buffer Size: 10000
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Collision Detection: On
In Process Workpiece: Off
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Maximum Angular Increment: 0.5000
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Figure. 2. Animation of aeroengine fan blade machining on human machine interface

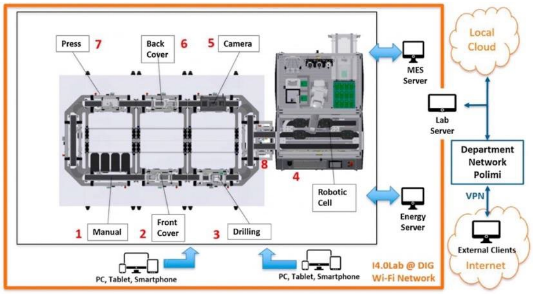

Figure. 3. Industry 4.0 Laboratory Production line (Eyre et al.2018)

3. Overview of Animation Technologies

Applicable DT animations technologies vary, depending on application, complexity level, and user requirements. This paper distinguishes between animation technologies and animation in DTs. The common characteristics of 3D environments in DTs that support visualization, interaction, and data responsiveness regardless of the platform used include: (1) synchronization with physical system data streams, (2) ability to reflect operational states through visual cues, (3) modularity for updating or scaling animations, and (4) support for user interaction through immersive interfaces. The most used platforms in DT applications include:

MATLAB is a frequent choice for simulation of DT in manufacturing due to strong computation capabilities and representing the system behavior (Pantelidakis et al. 2022).

Unity is a multipurpose platform with capabilities to create 3D animations and interactive simulations. Real-time rendering capabilities available in Unity have made it a perfect environment for developing virtual and augmented reality applications. In training environments, Unity is often used to create immersive experiences that mirror real-world manufacturing systems (Vladimir Kuts et al.2020). Figure. 4 shows an example of output signals and their states directly in running simulation in Unity software.

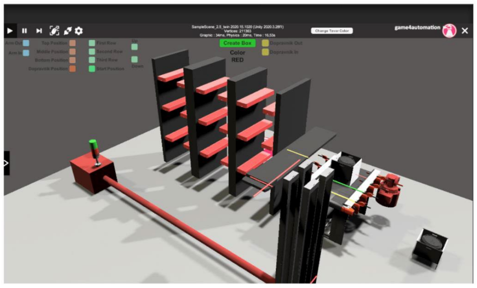

Figure 4. Output signals and their states in simulation model in unity software

Simio is discrete event simulation and scheduling software used in animating manufacturing processes. Since Simio can animate entire factory systems makes it a very good tool for visualizing material flow, machine use, and production scheduling (Eyre et al.2018).

Anylogic offers a 3D manufacturing simulation and allows to visualize, analyze, and optimize industrial processes (Any Logic 2024).

There are three steps in implementation of 3D simulation of manufacturing: model building (Wang and Abdoli 2025), simulation execution, and result analysis. The simulation environment is first constructed with pre-configured blocks of parts or CAD models. Simulation execution then takes place with testing of different process flow, analysis of production, and system performance analysis. Benefits of 3D simulation in use of DT comprise lower operational risk, higher automation testing and validation, and better planning, been identified to be of crucial importance in the future of smart manufacturing (Visual Component 2024).

Integration with NVIDIA Omniverse is a big step towards simulating 3D models, alleviating some animation limitations in manufacturing and logistic simulations. The photorealistic images with authentic-like refractions, shadows, and textures have not before been achieved with situational solutions in solutions. Integration with NVIDIA Omniverse makes AnyLogic effective in vision quality, interactivity, and synchronization in real-time in simulative models, with photorealistic animations as a feature. AnyLogic models can also be updated in live synchronizations, with dynamic agent motion and material flow(Any Logic 2024). Customizable functionality also allows users to substitute generic models with high-poly models, resulting in a more accurate interactive space. Anylogic is also compatible with Virtual Reality (VR), which allows stakeholders to interact with DT in person.

4. Applications for Digital Twin Animation

Animating the interactions between resources in production lines helps to track potential bottlenecks and predict failures to increase efficiency. Applications are most vital for high-stakes industries because to make sure that stakeholders are interested in any manufacturing project, the details of the systems can help to convince every investor and this can be seen in automotive and aerospace, where reliability is a must (Eyre et al.2018).

4.1 Training

Many training programs include DT animation and today’s technologies have involved VR/AR (Vongchaisaree and Abdoli 2025). Trainees in various fields engage with animated machinery models to achieve hands-on learning without any risks in working with real equipment. Animation in DT gives opportunities to make the training times shorter and errors to be reduced, beneficial especially when operating complex machinery (Müller et al. 2021).

4.2 Product Design

DT animation supports simulation, giving a wide view on how product works. For example, aerospace engineers use animations that model the lifecycle and stress factors in components like aeroengine blades where this animation has accurate data as real life so the producer will understand more about their product without even building it in real life. This allows for fast design changes with less dependency on real prototypes, helpful in reducing time and costs related to the market (Pantelidakis et al. 2022).

4.3 Safety

DT animation is crucial in enhancing operator and industrial machinery safety by simulating hazards and maximizing preventive measures, crucial in high-risk manufacturing, unsafe operations, or contaminated environments. Applying live data and forecasting analytics, DT animation allows testing unsafe scenarios, machinery interfaces, and environmental hazards, making it more effective to adopt preventive measures. Animated work areas can be constructed in DT for scenario analysis to study worker-device interfaces, evacuations in emergencies, and failure possibilities in high-risk areas like petroleum refinement, nuclear, and robotic lines, where prediction can promote compliance with occupational health and safety requirements. For instance, manufacturing personnel can train in virtual reality-based simulations on machine maneuvering. For equipment maintenance, DT animation can enhance the understanding of monitoring of wear and tears, and pre-breakdown failure detection. In aviation and automotive industries, DT animations allow producers to revalidate critical devices in critical scenarios and increase their reliability. DT animation in parallel to its provided data analytics in monitoring hazards in real-time will play a growing role in defining industrial safety.

5. Case Studies: Digital Twin Animation Across Platforms

Practical implementation of DT animation varies based on specific applications and tools used. This section presents three case studies using Unity, MATLAB, and Simio, each chosen for its distinct capabilities, aiming to curate a focused set of examples that capture distinctive roles animation plays. Fig 4b and 4c are not drawn from existing literature but are outputs of our scoping work for a larger research project that this study is intended to inform. Including these two figures provides a practical contrast to published cases and demonstrates how animation is being applied in ongoing industry. The intention is not to generalize from these few cases, but to use them as illustrative anchors for the broader patterns and issues that are explored in more depth in section 6.

The first case study is about controlling excavators remotely in a construction project. DT is used to enhance productivity and safety, along with providing training for remote excavator control. The platform used was Unity due to its strong physics engine and advanced 3D rendering capabilities that are crucial for safety aspect of the project, shown in Figure 5. VR/AR integrations can be incorporated to enhance the training. Although Unity provides a powerful platform, it requires extensive programming skills.

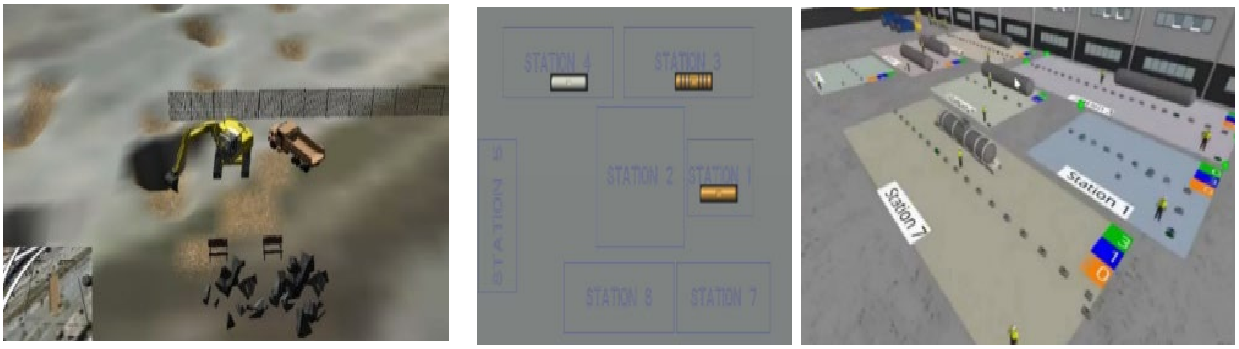

Figure 5. Animation case studies in various platforms: a) UNITY, b) MATLAB, c) SIMIO

Second DT was designed as a manufacturing facility for monitoring and control purposes by modeling different uncertainties while incorporating AI/ML capabilities for optimization. As shown in Fig 4b, MATLAB was selected, showing an abstract 2D animation. While MATLAB excels at modeling and simulation, its animation capabilities are limited as it requires custom coding to link simulation outputs to visualizations.

The third model, shown in Fig. 3c, was developed for the same manufacturing facility. However, DT aimed to apply scenario analysis to improve the overall productivity. Simio was chosen due to its abilities in modelling the manufacturing workflow along with detailed statistics in a simple and user-friendly interface. The animation was made in 3D by importing the CAD models, which are linked automatically to the simulation modules. Figure 5 demonstrates the project. As Simio shows great potential, its animation is primarily constrained to process-driven simulations.

Animation in DT depends on the platform used. Since animation is not the only objective when developing DT as shown on the different case studies, selecting the right platform requires balancing visualization quality with analytical capabilities and system integrations. Selecting the right platform depends on each case requirements and expected deliverables. A well-chosen tool ensures animation enhances both functionality and efficiency, making digital twins more impactful in industrial applications.

6. Emerging Technologies in Animation for Digital Twins

While section 4 focuses on individual case descriptions to ground the discussion, this section builds on that and previous critical review to identify generic insights and challenges that emerge across the examples and reviews.

VR/AR are new transformative technologies that can give better experience and view for the user. VR creates an immersive environment where users can interact with fully animated 3D environment in a DT to enable realistic experience. This technology can be useful in high-risk industries when training can be costly and has risk potential (Zheng et al.2024). AR enhances VR by superimposing digital information onto physical assets in real-time, thereby giving operators instructions on actual equipment. Integration will help to increase remote monitoring and real-time decision-making since operators can visualize data-driven insights directly on machinery they are working with (Tanberk et al.2024), Rabha et al. 2017).

By application of IoT and Edge Computing, real-time data from physical assets can be integrated into DT, helping operators to have a better overview of an operation (Park et al.2020). IoT devices used in manufacturing provide continuous streams of data to update DT based on physical asset status while edge computing allows processing of data closer to its source so that anyone who is handling these systems will have an accurate data of real physical systems rather than in centralized cloud servers because sometimes, cloud servers may delay and give inaccurate output. This reduces latency and permits DT to be updated more rapidly, which is crucial in applications requiring instant feedback and real-time monitoring (Tulani and Abdoli 2025). Combining IoT with edge computing makes DT animation more accurate and adaptive to real status of assets, enabling higher fidelity animation.

7. Research Gaps and Challenges

Data Communication/Synchronization of Physical and Digital Systems: Real-time synchronization between DT and physical systems frequently suffers from delays in data exchange between them, leading to misalignment between animated visualizations and actual physical processes (Park et al.2020). This discrepancy impacts reliability of animations in DTs because there is a risk in not recognizing the best outcomes for manufacturing process. Also, DT animation effectiveness will be reduced in real-time decision-making where the operator/engineer may find it difficult to create a solid decision based on non-synchronization data from the system. Studies focused on VR-based DT in the manufacturing sector highlighted some problems and one is that system may delay in data synchronization often result in inaccurate or lagging animations in virtual environments. This can affect system responsiveness when projecting physical system through VR (Martinez et al.2021). Another problem that can be faced due to such lags is DT animation for training, because this lag leads to incorrect interpretations (Park et al.2020).

Cost and Resource Constraints: High-fidelity animation development/maintenance can be costly, especially with advanced VR/AR integrated and considerable computational resources and specialized hardware are required (Martinez et al.2021). Most VR-based DT system papers point out high-quality animation requires a lot of computation resources and special equipment (Harvard et al.2019). Such high resource intensity in creating high-fidelity animations might disturb adoption of DT technology in smaller or resource-constrained industries.

Complexity for End-Users: Complex and highly detailed animations can render DT alien to non-expert users where it will impede their comprehension and interaction with the system. Poorly designed animations may flood users with more information than can be readily interpreted in training (Pérez et al. 2020). In VR-based training simulations, operators may have trouble interacting with complex 3D animations that impede their learning about the system. This is compounded by the lack of visual cues and intuitive interfaces, especially when trainees are not accustomed to the technology, so animations go against training process and overall effectiveness of DT being applied in an educational/operational setting.

Interoperability and Integration Issues: Integration of animation tools with other components of DT, such as ML/AI based decision support systems, IoT and real-time data feeds, can be a challenge. Many existing animation systems suffer from seamless integration, with disjointed or inaccurate animations that cannot reflect real-time changes in physical processes or cannot get output of decision-making modules and provide input to them. Several studies have reported difficulty in integrating IoT data into animation systems, leading to delayed updates or inaccuracies in reflecting changes of real-world conditions (Pérez et al. 2020). Accordingly, the value created by DT for visualization and decision-making is limited.

Scalability and Flexibility: Animating large manufacturing lines faces performance issues, which may lead to frame rate drops and lack of responsiveness—especially inside VR environments (Pronter 2021). The performance of large-scale DT animations—like factory floors or complex robotic setups—can be computationally intensive because it retrieves a lot of data that needs to render into the software, which usually results in lower frame rates, less responsive interactions, and a lesser user experience and accuracy of the system compared to physical system (Yilidiz et al. 2021). Accordingly, effectiveness of animation and simulation will decrease.

8. Discussion and Future Research

In this chapter, we take an initial step toward identifying possible directions for addressing the challenges surrounding DT animation by proposing practical entry points. While we acknowledge that some of the issues discussed are complex and deeply embedded in broader socio-technical contexts, our intent here is not to offer exhaustive solutions but to frame actionable starting points that can guide future research, particularly by proposing methodologies—including empirical, design-oriented, and interdisciplinary approaches—that could provide deeper insight into DT animation. Based on identified challenges and gaps, this paper outlines future research directions for DT animation in manufacturing, including key questions and proposed hypotheses.

8.1 How to Improve Real-Time Synchronization of DT Animations with Physical System to Realize Accurate Visualization in Manufacturing?

Hypothesis: This can be solved by optimizing data transfer protocols, reducing latency by integration with high-speed communication technologies such as 5G or 6G networks or low latency data channels. Edge computing is critical in cutting latencies in DT application by localizing data processing in relation to devices that generate it. Cloud-based data processing might lead to lags as data is transferred from devices to central servers, which is time-intensive. Industries can compute data with solutions like AWS IoT Greengrass and Azure IoT Edge, which minimizes response time. Where machinery is monitored in real time to optimize the maintenance by animation with fault visualization, then local computing with advanced analytics such as AI-based algorithmic power in addition to cloud-based solutions makes data speeds more productive, detection of outliers faster, and autonomous tweaks more seamless, making industrial activity more productive (Protner et al. 2021). However, cloud-based platforms can still offer benefits when it comes to scalability while addressing the data synchorinization issue. Some examples of platforms that form ecosystems for mapping physical assets with digital models are ThingWorx (PTC), Siemens MindSphere, and Microsoft Azure Digital Twins. ThingWorx is extensively utilized in industrial IoT scenarios. This software has functionalities that enable remote monitoring and process optimization while Siemens MindSphere is industrial automation and smart manufacturing-focused, with functionalities that assist companies in analyzing production data to enhance operational efficiency. Microsoft Azure Digital Twins is scalable digital representations-based that allows industries to design highly interactive models with animation features. All these platforms are supported by cloud computing to be scalable and process data in real-time, making these crucial in industrial scale-based applications when DT is enhanced by animation. Cloud-based DT solutions such as AWS IoT TwinMaker and Google Cloud Digital Twin enhance DT functionality a notch higher with high-performance computing, AI incorporation, and in-real-time exploration of data. AWS IoT TwinMaker helps businesses design, keep track of, and create digital copies of advanced systems with 3D visualization which is crucial for DT animation. Google Cloud Digital Twin also utilizes cloud computing to render in-real-time insights in manufacturing and logistic process enhancement. Cloud-based solutions allow organizations to manage enormous amounts of data efficiently with scalable/dynamic DT across industries (Sauer et al.2021).

Combining DT with both cloud-based IoT and edge computing can improve system integration with animation. Edge computing ensures minimal latency in real time visualization of the crucial and time sensitive aspects of the system, whereas computational power and scalability are made available from the cloud platforms to handle industrial scale simulations and animation when the decisions are not highly time sensitive. The combination of these technologies improves operational efficiency, and operational safety and automation, enhancing DT's position in Industry 4.0 and smart manufacturing. This makes DT animation more synchronous, creating a real-time visualization that is more realistic for timely decision-making and monitoring (Park et al. 2020).

8.2 How to Minimize the Cost and Resource-Intensive Nature of Developing High-fidelity, Interactive DT Animations in Manufacturing?

Hypothesis: Implementing modular VR/AR frameworks and adjustable animation fidelity settings can allow for scalable quality levels where these levels can significantly reduce costs and computational demands associated with high-fidelity animations. This approach will make DT animations more accessible to small and medium-sized manufacturing enterprises and companies with limited budget or technical skills (Martinez et al.2021).

A modular structure in DT facilitates its maintenance. Having an animation module in a DT allows recycling of the existing animation module and not developing a new one for a new project within a manufacturing system. In this approach, pre-configured units are available that are generic in industrial processes, i.e., robotic assembling, material transfer, and production lines. Moreover, when duplication of models is reduced, development is speeded up, and resources are reduced, and the entire DT will be less complex and computationally resource intensive. Use of ready-for-use models from available repositories or industrial repositories eliminates time-consuming in-house modeling, maximizing DT animation efficiency (Picone et al. 2022, Abdoli 2023).

Another effective strategy is dynamic animation fidelity scaling according to computational requirements in real time and according to requirements from users. Not necessarily in all application scenarios high-fidelity animations with high-fidelity textures, physics-based simulations, and in-real-time ray tracing will be necessary. Dynamically scaling animation complexity will allow manufacturing companies to allocate computational resources towards important visualization activities with reduced costs on hardware and power. Such a feature is especially valuable in DT platforms that are in the cloud because high-fidelity models are both power and cost intensive. Moreover, the application of open-sourced platforms and software can also aid in evading expensive commercial software licenses, making cost-effective DT development a reality. Open-sourced simulators in 3D design, Blender; in physics-based simulation, Gazebo; and in CAD design, FreeCAD are some cost-effective solutions that can be utilized by those with smaller budgets as much as technical proficiency. Open-sourced IoT platforms as much as APIs also enable seamless interfacing between DT with sensor data from the physical world free of cost, removing the need for expensive commercial solutions (Gao et al. 2023).

8.3 How to Simplify DT Animations to Improve Usability and Comprehension, particularly For Training in the Manufacturing Sector?

Hypothesis: One way to address this question is by incorporating intuitive visual cues and interactive tutorials. Because the operator may find it hard if they do not have any guidance to start with in DT animation. Providing user-friendly interfaces can enhance usability and understanding for non-technical users, better training outcomes, higher engagement and improving operational efficiency in training contexts (Pérez et al. 2020).

Simplification of DT animations is crucial in making usability/comprehension more effective in the manufacturing sector. While high-fidelity animations can produce highly detailed and accurate models of industrial processes, these can also contribute to complexity and mental load, which can be difficult for trainees, particularly those with little technical background, to interact with a comprehended system. An advantage of simplified animations is that trainees' mental load is minimal. In advanced manufacturing, users need to deal with high amounts of information in a short time from machinery operation to procedure safeguards and workflows in a process. Overly detailed DT animations can be intimidating to users, leading to high learning curves and lowered engagement. Animations simplification, as with the utilization of color-coded signs, progressive layering, and interactive guiding, makes trainees' attention focused on key points in a simplified manner. Such simplification can be hybridized with Explainable AI (XAI), provides stepwise explanations regarding system behaviors and decisions' reasoning, making DT results understandable. In addition to ease of comprehension, interactive training and adaptive training can boost training impact. Trainees can interact with digital duplicate animation models in turn, modify parameters in a live manner, and be equipped with prompt feedback on moves.

User-friendly interfaces are crucial in making DT animations accessible to non-professionals. Many operators will not have advanced software or programming skills, so training platforms must be intuitive, graphically simple, and simple to navigate. Such features as drag-and-drop interfaces, verbal instructions, and AR/VR-supported walkthroughs can enhance usability and assist trainees in becoming familiar with DT-based training in a short amount of time. Addition of multimodal learning features, such as narration, gesture-based interfaces, and augmented overlays supports increased engagement and learning. Adaptive learning solutions, AI-based feedback and interactive models with VR have a more central role in restructuring training in smart manufacturing ecosystems as DT technology keeps improving (Sepasgozar 2020).

8.4 How to Integrate Animation Tools with IoT and Real-Time Data in DT for Seamless Data Visualization?

Hypothesis: Standardization of data protocols and middleware in every software that will be used to monitor the animation will enhance interoperability among the animation tools in a DT system where any modification in real time will be reflected in animations. This reflection can enhance overall manufacturing system responsiveness because the operator can detect any change that happens in physical systems by analysing the animation in digital systems, as suggested by Warke et al. (2021).

Riding on standardized communications protocols, on cloud infrastructure, with the incorporation of RESTful APIs (Representational State Transfer APIs), and utilization of Software Development Kits (SDKs), industries can design scalable and efficient DT infrastructures in manufacturing and industrial automation. Protocols like MQTT (Message Telemetry Tequeing Transport) and OPC-UA (Open Platform Communication Unified Architecture) are important facilitators in data transfer between digital models and physical devices. Because MQTT is a light publish-subscribe protocol that is highly used in industrial IoT solutions as it can efficiently transfer sensor data over constrained networks with little utilization of bandwidth. It is applicable in monitoring machines in real time or energy management visualization in smart manufacturing. OPC-UA is a more advanced, secure, and scalable form of communication that allows interoperability between sensors, machines, and enterprise applications. With these protocols, DTs are made accessible with reliable, real-time information on environmental conditions, operational parameters, and on machinery performance, ensuring animations are synchronized with real-world process (Nam et al. 2023).

Cloud platforms such as AWS, Microsoft Azure, or Google Cloud play a key role in scaling DT solutions in consolidating IoT data, executing in-real-time analytics, and dynamically updating models. For instance, AWS IoT TwinMaker supports ingestion, visualization, and storage of manufacturing data (Holliman et al. 2019).

To facilitate two-way data transfer between DT animations and physical devices, industries are moving to employ RESTful APIs. A standardized interface in fetching, processing, and displaying live data in a format that can be interpreted makes RESTful APIs a standardized interface. A standardized interface makes it a central component in DT architecture. For example, robotic arm position data can be transferred via an API to synchronize a model in a simulation, making monitoring of positional accuracy, speed oscillations, and collision risks possible. RESTful APIs facilitate DT's compatibility across multiple platforms, so DTs can be integrated with third-party visualization dashboards, and AI-based anomaly detection (Hietala 2020). The pioneer vendors of DT such as Siemens, Dassault Systèmes, and PTC ThingWorx utilize Software Development Kits (SDKs). Pre-integrated blocks, libraries, and automation functionality in SDKs allow high-fidelity interactive simulation development. Utilization of SDKs accelerates DT development, reduces laborious code writing, and integrates complicated system behaviors in animation models with ease. Customization flexibility and magnitude in SDKs allow DT to be tailored according to requirements. Siemens' MindSphere SDKs, for instance, provide industrial connectivity blocks to allow manufacturing simulators and IoT sensors to be synchronized in real time. Similarly, 3DEXPERIENCE platform SDKs from Dassault Systèmes provide advanced visualization functionality in virtual prototyping, process simulation, and AI-based decision making (Gil et al. 2024).

8.5 How to Realize Scalability of DT Animation to Represent Large/Complex Manufacturing Environment Effectively without Losing Performance?

Hypothesis: Using distributed computing architectures and advanced rendering methods in animation systems can contribute to solving this problem, while DT remains responsive and efficient in data-intensive applications (Yilidiz et al. 2021).

A DT must be able to collect, process, and display data from IoT devices efficiently to deliver real-time insights with interactive simulations. The convergence consists of tapping into industrial IoT platforms for cloud-based data management, high-performance visualization software for interactive simulations, and scalable data processing infrastructures to manage high-speed streams of data. Cloud platforms are critical in consolidating IoT data, making it scalable, and providing remote accessibility to DT. As explained, the established industrial IoT platforms, such as PTC ThingWorx, connect with IoT sources, offering real-time updates, and interactive 3D models of complex manufacturing systems. Likewise, Siemens' MindSphere as a cloud-based industrial IoT platform, supports DT deployments on a massive scale while offering visualization. Such platforms keep DT' data-based, updated, and scalable for industrial usage (Adamenko et al. 2020).

Visualization's effectiveness is enhanced with interactive and photorealistic 3D visualization. Unity 3D is a leading development platform in making interactive simulations, VR training capsules, and 3D animations in real-time, hence an effective platform for visualization in manufacturing contexts. Unreal Engine is a high-performance visualization platform that is compatible with photorealistic animations, physics-based simulations, and interactive digital worlds, hence highly effective in in-depth process visualization, operator training, and scenario-based testing in real-time. Autodesk Forge is a visualization platform that is in the cloud with compatibility with data-driven 3D modeling, with CAD integration, and visualization in industrial assets, with seamless collaboration and DT exploration. Union of these visualization platforms and DT models can enhance engagement, training speed, and improve decision-making in manufacturing when animation is integrated with DT (Adamenko et al. 2020).

Data Processing Architectures Scalability in Digital Twinning Efficient data processing is essential in handling massive DT deployments with event-triggered automation, real-time analytics, and secure transactions. Apache Kafka is a distributed event streaming platform that is favored by high-throughput fault-tolerant data processing, which can enable DT to process a million points from IoT devices. Sharding and partitioning strategies accelerate speed by distributing workloads across multiple servers, which makes DT scalable and respond with a quick reaction. Such strategies are highly effective in handling complex manufacturing scenarios, which entail AI-based anomaly detection, and prediction models that are based on efficiently handling massive data.

9. Conclusion

To the best of the authors' knowledge, this study is one of the first ones that investigates application of animation in DT in manufacturing sectors. The existing concepts, tools, and application areas were reviewed. Based on a critical review, research questions and hypothetical solutions were offered. So, this study makes valuable contributions to animation of DT in I4.0, such as pursuit of better real-time synchronizations, cost reduction by using scalable animation strategies, and ease of use by the end-user. These indeed fill some critical gaps in current DT systems and open fresh perspectives for the wider diffusion of this technology into manufacturing. Integration of DT animation with running automation systems could have unforeseen complications while scaling up for big and complex operations. Because of this, future studies are recommended to extend real-world testing, investigate further advanced AI-driven optimizations of the DT animation model, and develop standardized protocols which would allow better interoperability of animation tools in different industrial scenarios. Based on that, subsequent studies could further develop functions and effectiveness related to DT animation systems inside and outside the manufacturing domain.

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