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Gamification and Digital Twins: A Synergistic Approach to Enhancing Manufacturing Processes in Industry 4.0

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ABSTRACT

Industry 4.0 has transformed manufacturing through digitalisation, yet challenges like workforce engagement and process inefficiencies remain. This paper explores the synergy between gamification and digital twins as a human-centric solution. By integrating the immersive, data-driven capabilities of digital twins with the motivational power of gamification, we demonstrate the physical setup and outline the synergy mechanisms via practical case studies from the Hong Kong Productivity Council (HKPC); they demonstrate applications such as gamified simulations for skill development, real-time process optimisation, and remote engagement. We also describe the technology enablers for synergy adoption. Challenges like technical barriers, human resistance, and economic barriers are also addressed. This integration not only enhances productivity but also empowers workers, paving the way for a more engaging and sustainable future in smart manufacturing.

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1. Introduction

Industry 4.0 has initiated a transformative era of manufacturing, characterised by cyber–physical systems, smart automation, data-driven decision making, and data autonomous. Enabled by technologies such as sensors, human–machine interfaces (HMIs), networking, and big data analytics, Industry 4.0 promises unprecedented efficiency, agility, and customisation in production processes (Kagermann et al., 2013). At the heart of this transformation lies the digital twin—a virtual replica of physical assets, processes, or systems that enables real-time monitoring, simulation, and optimisation (Grieves, 2014). From predictive maintenance to virtual prototyping, digital twins have become indispensable tools for modern manufactures (Tao et al., 2018).

As factories become more advanced and smarter, a significant challenge persists: human engagement. While digital twins excel at streamlining machine-to-machine communication, they frequently struggle to connect human operators with intricate, data-intensive environments. Workforce skill gaps, resistance to new technologies, and the cognitive overload caused by real-time data streams hinder the full potential of Industry 4.0 (Romero et al., 2016). Traditional training methods and static dashboards struggle to foster active participation, leaving workers disengaged and underutilised in increasingly automated workflows.

This is where gamification—the application of game design elements in non-game contexts—emerges as a compelling solution. By integrating mechanics such as points, badges, leaderboards, and narrative-driven challenges, gamification taps into intrinsic human motivators like competition, achievement, and mastery (Deterding et al., 2011). Recent studies demonstrate its efficacy in industrial settings, from improving safety compliance to accelerating skill acquisition (Pereira et al., 2019). However, gamification's true potential remains underexplored in regard to its synergy with digital twins, particularly in addressing Industry 4.0's human-centric challenges.

This paper investigates how the fusion of gamification and digital twins can create adaptive, human-in-the-loop systems that enhance manufacturing processes. We posit that gamification transforms digital twins from passive monitoring tools into dynamic, engaging platforms that empower workers to interact with virtual models in meaningful ways. Such integration not only accelerates decision making but also fosters a culture of continuous improvement and innovation. In addition, this paper reviews the existing industrial use cases constructed by the HKPC.

This paper addresses three key questions:

1. How can gamification enhance the usability and effectiveness of digital twins in Industry 4.0?
2. What are the measurable impacts of this synergy on workforce engagement and operational efficiency?
3. What challenges arise when implementing gamified digital twin systems in manufacturing sectors?

Through the case studies of the existing industrial applications constructed by our team and the Hong Kong Productivity Council, we demonstrate that this synergy offers a path to human-centric Industry 4.0. By bridging the engagement gap, manufacturers can unlock new levels of productivity, sustainability, and adaptability.

2. Implementation Framework

The integration of gamification and digital twins represents a fundamental shift in human–machine collaboration. This synergy utilises the immersive and data-driven digital twins with gamification motivational features, creating a closed-loop system which enhances both operational efficiency and workforce engagement; the features driving the synergy and the framework are outlined with the actual setup.

2.1. Synergising Gamification and Digital Twins Methodology

To drive the synergy, the following mechanisms/features are included:

- Real-time feedback loop

Through the Internet of Things (IoT) sensors, simulation, and analysis, there is continuous data from the digital twin. Gamification converts the data into actionable feedback for the workers; the actions drive the update of the digital twin forming the loop.

- Immersive Interaction

The virtual and human-centric environment provides the risk-free environment for process simulation. The virtual environment can be interacted with by the advanced human–machine interfaces, like virtual reality (VR) glasses. Gamification introduces structured tasks with an immersive experience.

- Collaborative Problem Solving

A multi-user platform enables cross-functional teams to access shared virtual models. Gamification encourages team collaboration through cooperative targets.

2.2. Framework and Set Up

A three-layer framework was set up to deploy the applications and demonstrate this synergy (Figure 1 shows the framework of the synergy).

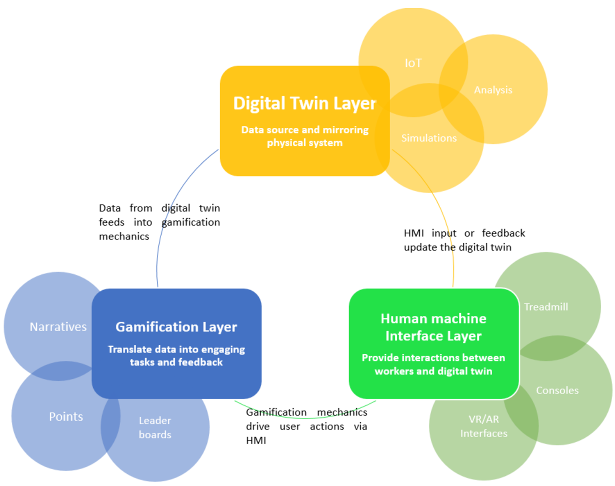

Figure 1. Gamified Digital Twin Framework.

This framework operates based on the theoretical principles of human-in-the-loop cyber–physical systems (Pereira et al., 2019), where operators are active participants driving the gamification mechanics via human–machine interfaces rather than passive observers.

The digital twin layer contains the IoT sensors, simulation of the physical system, and data analytics, and serves as the data source of the gamification layer; the gamification layer involves the gamification features, like narrative-driven tasks, points, leaderboards, etc. translating the data into engaging tasks; the operators can provide actions to refresh the digital twin via a human–machine layer by the components of VR/augmented reality (AR) interfaces, consoles, treadmills, etc. Figure 2 below shows the equipment setup of the application development and implementation.

Figure 2. Setup used for the application development and implementation presented in this paper (Application: Remote Industrial Robot Teaching Enabled By VR).

3. Industrial Application Studies

3.1. Application 1: Remote Industrial Robot Teaching Enabled By VR

The application is developed jointly with the partner in Foshan, which provides robotic application services to various manufacturing sector clients. The application is to address the challenges in robotic programming efficiency, lack of proficient robotic operators, safety, and cross-regional collaboration. The system integrates a physical robotic manipulator deployed at the Foshan factory site with a hosted digital twin in Hong Kong, enabling remote programming through VR interaction.

The physical robotic manipulator, configured for tasks such as material handling, is programmed using traditional robotic programming language, which is similar to C programming. A digital twin of the manipulator, which is hosted in the HKPC, synchronises real-time data with the physical system via internet protocols and a self-developed digital twin data processor, which transforms the digital twin data to the motion instructions of the robotic manipulator. The digital twin replicates the physical setup, robot kinematics, and operational constraints, providing a realistic simulation platform (Figure 3 shows the topology of the application).

Figure 3. Remote Industrial Robot Teaching enabled by VR.

Operators interact with the digital twin through a VR head-mounted display (HMD) and the treadmill, allowing for intuitive drag-and-jog programming. The VR HMD provides the immersive virtual environment, and the treadmill is the VR movement console. Within the virtual environment, operators can manually modify the robot's end-effector path by dragging waypoints or incremental jogging joints, with haptic feedback from the VR console providing enhanced precision. The generated twin action data is sent to the digital twin data processor and controller in Foshan; the data is translated into native robotic language commands, generating collision-free paths that conform to the physical robotic manipulator's constraints. The application provides gamified interactive tutorials with a tracking bar. New users can complete the VR tutorials with the physical robotic manipulator connection setup. Offline simulation can also be conducted in the human-centric ways by using the VR interface.

Programmed paths are sent to the physical robotic manipulator via the internet connection, ensuring synchronisation between the digital twin and the physical system. The framework enables engineers in Hong Kong to conduct debugging and optimisation remotely, reducing travel expenses and downtime. The cross-regional ability showcases the feasibility of decentralised manufacturing workflows, leveraging the digital infrastructure linked to Hong Kong and Foshan's industrial capabilities.

Key advantages include enhanced safety and accessibility, as operators can program hazardous or complex tasks remotely, minimising their exposure to unsafe environments. Reduced downtime is achieved through the immediate deployment of virtually tested programs, significantly lowering production interruptions. Collaboration efficiency is increased by allowing multi-site teams to concurrently access the digital twin for training or troubleshooting, promoting cross-disciplinary innovation. Additionally, scalability is ensured with the hosted twin supporting simultaneous access by multiple users, enabling large-scale industrial adoption. The partner has applied the solution to a 3C accessories OEM factory in Dongguan; the preliminary feedback highlights an 88% reduction in production line changeover cycle time (9 days to 1 day) and a 4-fold increase in productivity (20,000 pieces/day to 80,000 pieces/day), underscoring the solution's practical impact. This case highlights how digital twin and gamified VR technologies can transform and connect geographically and operationally separate areas, presenting a scalable framework for smart manufacturing ecosystems.

3.2. Application 2: i4.0 Digital Lean in the Metaverse

The second application presented is i4.0 Digital Lean in the Metaverse which is developed by the HKPC team to demonstrate the virtualisation for manufacturing optimisation. A fully immersive advanced manufacturing innovation is able to achieve cost reduction through the collaborative optimisation of production lines in the Metaverse by implementing the HKPC-patented i4.0 digital lean methodology. It offers a low-cost and quick-win solution for various manufacturing industries that visualises real-time optimisation. Through HMD and VR treadmills, the production parameters are analysed by data analytics technology without the need for other physical equipment and are not hindered by geographical limitations for concurrent use.

This application simulates actual production lines and their related manufacturing processes in the Metaverse environment with adjustable parameters for changing the configurations to optimise productions. Digital Lean is one of the key Industry 4.0 technologies to optimise production efficiency and reduce waste. All production data of the virtual production lines will be generated and analysed so that bottlenecks are found ahead of time and further adjustments can be performed at an early stage. The required time and costs for the Plan-Do-Check-Act, lean improvement, or production testing can be greatly reduced. By integrating the gamified components, leaderboards, and point and progress bars for motivators, this demonstrates the synergy of gamification and digital twins. This application is recognised by the awarding bodies of international awards, like the Edison Award (Silver), the finalist of R&D100, and the gold medal of the Geneva Award.

With the use of all four key enablers of Industry 4.0, namely smart sensor, human–machine interface, data, and networks, the Metaverse platform can re-create any digital lean productions and solutions, with all the production data being collected, analysed, and visualised in real time. With this application, multiple users can connect to the virtual digital lean production line in the Metaverse through HMD. The virtual production line is labour intensive, with two roles for the users: worker role and manager role. Users in worker roles will be trained as workers in the assembly workstation before entering the production line. After training, users will be placed in the workstation to perform the assembly process. Their action and production data will be collected and visualised in the dashboard in real time. Users in manager roles can review the production data and perform adjustments to improve the efficiency of the entire production line. The adjustable process and environmental parameters include machine processing parameters, jig and fixture holding operation, production line height, production line speed, and environmental factors such as lighting, humidity, temperature, etc. Figure 4 below shows an application which demonstrates i4.0 Digital Lean in the Metaverse.

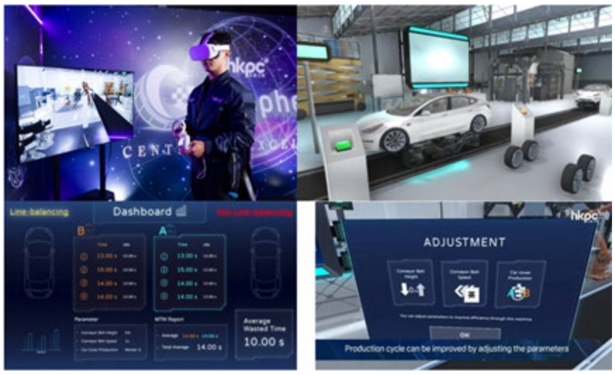

Figure 4. i4.0 Digital Lean in the Metaverse.

The application enables the visualisation of physical “Digital Lean” production, allowing factories to lower their trial costs by first completing line balancing and testing in the Metaverse, and avoiding the excessive time and costs spent on physical equipment and facilities to be set up when compared to the traditional trial and error optimisation method. The virtual production line in the Metaverse will also perform accurate and true-to-life processes. Thus, the necessary parameters and accurate improvement insights can be directly applied to the actual production line. The overall ramp-up time has significantly decreased. Also, the virtual engineering enabled by Digital Lean can help manufacturers strengthen the overall occupational health and safety and reduce risks in the workplace. By creating ergonomically and appropriately designed workstations and steps along the production line, the health and safety of the workers are well catered for, and this is how the new concepts of “i4.0 & Beyond” and “human-centric production” can be realised. Furthermore, this application encourages people to explore the possibilities of revolutionising manufacturing processes by taking advantage of the Metaverse. In the past, manufacturers may have had to acquire different types of machinery to improve their productions, with the risk of not achieving a satisfactory outcome, and hence a recurring trial and error process which is time consuming and cost intensive. With this application, manufacturers can easily try out different machines and match them in order to find out the optimised configurations.

4. Technology Enablers

The seamless integration of gamification and digital twins in manufacturing hinges on five interconnected technological pillars.

4.1. IoT and Edge Computing

IoT drives industrial evolution through seamless connectivity between physical assets and their digital counterparts. By enabling real-time data exchange across systems, IoT empowers applications such as the Digital Lean manufacturing case study, where IoT devices feed machine performance data into virtual twins—facilitating gamified "predictive maintenance challenges" where operators compete to troubleshoot simulated equipment failures. As industries rapidly adopt IoT to interlink devices on an unprecedented scale, they face significant challenges: transmitting large amounts of data to centralised cloud servers puts a strain on bandwidth and computational resources, and the diverse protocols of various devices make unified management difficult.

Edge computing overcomes these limitations by decentralising data processing. Positioned at the network periphery near data sources, edge nodes integrate computing, storage, and networking capabilities to deliver localised, real-time analytics—eliminating the reliance on cloud round-trips. This architecture reduces latency levels while slashing cloud processing loads. By processing sensor data locally, edge systems enable agile decision making for time-sensitive operations, meeting Industry 4.0’s demand for adaptive, real-time optimisation.

4.2. AI-driven Analytics

AI-driven analytics complements the infrastructure which personalises gamification mechanics by correlating operator performance with historical datasets. AI and machine learning have redefined industrial analytics by processing vast datasets at unprecedented speeds, uncovering patterns imperceptible via conventional methods. Unlike manual analysis, AI-driven tools excel in three critical dimensions: scalability to manage petabyte-scale manufacturing data, precision in predictive modelling, and mastery of nonlinear relationships within multivariate systems like complex optimisation problems or simulations. By automating labour-intensive manual analysis, AI liberates engineers so that they can focus on strategic optimisation.

4.3. Digital Twins and Extended Reality (XR)

The convergence of digital twins and XR serves as the backbone of the Industrial Metaverse (IM) platform, enabling seamless human–machine collaboration and data-driven optimisation. These technologies bridge the physical and virtual worlds, addressing Industry 4.0's dual challenges of operational agility and workforce engagement. The digital twin technology provides a digital representation of a physical asset with data linkages for the inspection, monitoring, and prediction of complex processes or systems, while extended reality offers real-and-virtual combined environments for human users to interact with machines (Tu, Xinyi, 2023).

Digital twins are dynamic, data-rich virtual replicas of physical systems that enable real-time monitoring, simulation, and predictive analytics. As highlighted in the Frontiers review, digital twins transcend traditional CAD models by integrating IoT sensor data, machine learning, and historical performance metrics to create living simulations of production environments (Smith et al., 2023). XR—encompassing VR, AR, and Mixed Reality (MR)—transforms how humans interact with digital twins.

5. Challenges and Limitations

The integration of gamification and digital twins in manufacturing, while transformative, faces challenges that span technical, human, and financial domains. These limitations are particularly pronounced in complex implementations.

5.1. Technical Challenges

Digital twins require real-time data from the physical machine and IoT sensors via the internet, creating vulnerabilities to cyberattacks (Zhou et al., 2020). Gamified digital twins track workers' performance metrics risk exposing sensitive operational and personal data. Many small to medium-sized enterprises (SMEs) still operate Programmable Logic Controllers (PLCs) using proprietary, which lack native compatibility with 3D-based gamification engines or cloud APIs. Connecting a gamification engine with proprietary industrial IoT frameworks requires standardised APIs and middleware (Tao et al., 2019). A study by McKinsey shows that 70% of Industry 4.0 pilots fail due to incompatible legacy infrastructure (McKinsey & Company, 2022). Gamification requires low-latency processing of digital twin data. Limited GPU capacity for VR simulations remains a bottleneck for SMEs (Grieves, 2021).

5.2. Human Challenges

Older workers may struggle with the VR interfaces or new technologies. The point or badges can boost short-term engagement, but this extrinsic motivation may undermine the intrinsic motivation if the rewards become the only focus. This point-driven justification may be over and reduce the creativity in problem solving (Deci & Ryan, 2000). Additionally, gamified systems may overwhelm users with excessive data, such as notification, sound, and data visualisations.

5.3. Economic Barriers

SMEs face significant financial hurdles in developing high-fidelity digital twins and custom gamification systems. The upfront costs of deploying immersive digital twins, XR interfaces, and IoT infrastructure often exceed the capital reserves of SMEs, which typically operate with tight margins. For instance, retrofitting legacy machinery with IIoT sensors and edge computing systems can incur costs exceeding 30–50% of annual IT budgets for ASEAN manufacturers (ASEAN Digital Transformation Report, 2023).

6. Future Directions

The integration of gamification and digital twins is still in its nascent stage. Beyond Industry 4.0, future manufacturing is also emphasising human-centricity and sustainability; this synergy will play an essential role in shaping the innovation of the manufacturing. The key potential directions for the future R&D and implementation is to leverage AI. By integrating AI, AI assistance could be involved in the solution providing customised guides, insights, and tailoring gamification mechanics according to individual operators' preference and skill levels adaptively; the AI algorithms could amend the challenge difficulty in digital twin simulation according to real-time performance data (Klock et al., 2020). Another is focusing on the occupational health and safety: AI-enabled digital twins can predict worker fatigue and machine health status, and trigger gamified intervention.

7. Conclusion

In this paper, the practical setup for combining gamification and digital twins has been outlined. Through the industrial application cases from the HKPC, we have shown how digital twins synergised via gamification can optimise the manufacturing processes, and prepare workforces for the rapid evolving environment which requires resilience; some measurable impact, like the production line changeover cycle time and productivity, has been mentioned, which further demonstrates the effect of this synergy. The enabling technologies are also described. Yet, technical challenges, human factors, and economic factors must be addressed to ensure the success of the synergy adoption. The convergence of AI technologies will provide more inclusive and personalised opportunities for application scenarios. In conclusion, the role of the synergy of gamification and digital twins will only become more important when future manufacturing places emphasis on human–machine collaboration and sustainability.

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