Mechanical Engineering Advances 2025, 3(4), 3350.
doi: https://doi.org/10.59400/mea3350

Article

Enhancing learning experience of manufacturing through metaverse—development and demonstration

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CITATION

Anadkat D, Sama M, Sata A. Enhancing learning experience of manufacturing through metaverse—development and demonstration. Mechanical Engineering Advances. 2025; 3(4): 3350.
https://doi.org/10.59400/mea3350

ARTICLE INFO

Received: 9 June 2025
Revised: 6 November 2025
Accepted: 9 November 2025
Available online: 1 December 2025

Abstract: Integration of disruptive technologies like Metaverse, AR/VR, Digital Twin, etc., with manufacturing education is revolutionising the learning experience and bridges the gap between traditional and hands-on practice. This paper focuses on the development and demonstration of an immersive interactive environment in manufacturing processes, specifically in the Vertical Centrifugal Casting (VCC) and Tungsten Inert Gas (TIG) welding. Integration of immersive environment with traditional manufacturing processes allows the learners to interact with a real-physical setup, real-world scenarios, and optimize the process in a virtual risk-free environment from a distant place. The proposed system demonstrates the real-time monitoring and controlling of data using IoT, data collection using DAQ, as well as digital twinning of the system for improved learning and operational efficiency. This integration allows users to monitor and operate different process parameters, like tuning of VCC, mold rotation, metal pouring, and practicing metal pouring, as well as adjusting the parameters in real time. This study highlights the significance of imparting manufacturing education through immersive technologies, resulting in improved experiential learning, safer practice opportunities, and enhanced student preparedness for Industry 4.0 environments, as validated through system validation. This study revolutionizes conventional industrial education with Metaverse applications, facilitating a more engaging, accessible, and efficacious training paradigm aligned with the Sustainable Development Goals (SDGs) 4 (Quality Education) and 9 (Industry, Innovation and Infrastructure).

Keywords: manufacturing education; immersive technologies; Industry 4.0; AR/VR; enhanced learning; metaverse; Sustainable Development Goals

1. Introduction

The development of the latest technologies in education and their convergence has become highly significant since the manufacturing sphere is already moving towards Industry 4.0. Such technologies as Virtual Reality (VR), Augmented Reality (AR), and the Metaverse not only redefine the methodology of learning but also equip learners with an increasingly digitalized world of manufacturing [1]. The new technologies assist learners in acquiring the skills they need to become successful in the present-day industries and allow them to experience working with complicated systems, such as IoT-based manufacturing, robotics, and predictive maintenance. Immersive technologies are transforming the process of learning through supporting manufacturing learning to innovative and industry-ready manufacturing professionals [2,3]. The Implementation of SMART Factories means that the workforce would be competent in automation, sensor integration, and data analysis, thereby reinforcing that immersive learning is important.

Learning manufacturing requires learners to have both theoretical knowledge and hands-on skills [4]. Understanding material properties, equipment functions, and the interrelatedness of production systems is an essential capability that forms the core competency. Traditional workshops face many limitations, such as constraints of space and time, and safety hazards, which may lead to reduced learning depth and effectiveness.

With the help of Metaverse, these constraints can be overridden with virtual spaces through which learners can interact with machinery, explore industrial procedures, and emulate situations without material constraints [5–7]. Using the metaverse, learners can prepare the model of mold in casting, study the metal flow, as well as explore the defect formations like shrinkage or porosity in casting, whereas they can practice TIG, MIG, or Arc Welding process in a secure environment in welding. The ability to imagine and reproduce such processes increases grasping and prepares learners for complex real-world applications [8–10]. The direction relates to the Sustainable Development Goals (SDG 4: Quality Education and SDG 9: Industry, Innovation and Infrastructure), as it helps to provide equitable access to high-quality manufacturing education and create technologically advanced quality training ecosystems.

2. Learning-theory foundation for immersive manufacturing education

Education in manufacturing should not only involve education at the conceptual level but also the development of progressive skills, which is realized through continuous, controlled exposure to the industrial functions and procedures. To make sure that the suggested metaverse-facilitated learning environment can be consistent with the existing pedagogical principles, the present research is based on a multi-theoretical conceptualization, combining Experiential Learning Theory (Kolb), Situated Learning Theory, the Cognitive Load Theory, and the theory of Skills Transfer.

The Experiential Learning Theory holds that successful supplementation of skills takes place in a cycle that comprises concrete experience, reflective observation, abstract conceptualization, and active experimentation. The immersive conditions designed to support Vertical Centrifugal Casting (VCC) and the TIG welding clearly facilitate this cycle by allowing the learner to (i) simulate the conditions of real processes, (ii) observe the effect of parameter variations, (iii) conceptualize the relationship between processes and defects, and (iv) engage in decision-making regarding their safe operations virtually.

The system is also based on the Situated Learning Theory, which underlines the fact that significant learning takes place in real-life situations. Recreating industrial casting and welding workplaces, sensor data, and digital twins, and being able to adjust process parameters, the proposed metaverse platform will expose learners to the context-rich settings that are closely related to the conditions on the real shopfloor. This will allow creating tacit knowledge associated with the metal flow, defect formation, heat distribution, and the stability of welding, which can hardly be learned in a traditional classroom.

Cognitively, the immersive system is meant to lighten the extraneous cognitive load through the provision of intuitive visualizations, direct manipulation interfaces, real-time feedback, and spatially embedded information about the processes. By reducing the cognitive load of interpreting abstract information or visualizing the unobserved processes, the learners will be able to pay more attention to the main concepts of manufacturing and the decision-making strategies.

Lastly, the learning environment clearly facilitates skills transfer, where the learners can move up the ladder between virtual practice and physical practice. This is made possible by faithful rendering of sensor feedback, natural actuator behavior, precise digital twin behavior, and by means of controlled exposure to industrial effects like heat flow, molten metal fluid behavior, and sensitivity of welding parameters. Initial user testing proves that the virtual-to-physical transition can be considered smooth, with students stating that they are more ready to work with real equipment.

The proposed system, through these interrelated theories of learning, is deliberately designed to enhance conceptual knowledge, operative mastery, and the accuracy of decision-making in manufacturing education to the greatest extent possible.

In manufacturing, metal casting is one of the oldest manufacturing processes and has a great impact on industrial applications. Metal casting involves the heating of a metal or an alloy to its melting point and then pouring the molten material into a mold to gain a desired shape. Over time, casting has developed to accommodate components of varying parameters such as dimensions, shapes, and other mechanical properties, leading to the development of some special techniques such as pattern, mold, melting procedures, and solidification. Casting has also been made more accurate with reduced defects and better efficiency due to progress and application of Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA). Cylindrical components, such as pipes, tubes, pistons, and aluminum cylinders, are produced with the help of a special casting process known as Vertical Centrifugal Casting, where the mould is rotated around a vertical axis [11]. Castings made under this action have high density, low porosity, and enhanced mechanical properties [12–14]. VCC and other advanced casting processes, however, demand close control of parameters such as mould temperature, pouring temperature, and rotating speed. Knowledge in these processes entails an in-depth knowledge of the properties of materials to be used, process management, and methods of defect prevention. The casting of the past is based on the capability and art, whereas the contemporary progressions, such as Digital Twins, the IoT, and computer modelling, improve accuracy and efficiency in the casting process. These technologies provide real-time monitoring, preventive maintenance, and data-driven decision-making, which increase the quality of production and minimize waste [15,16].

Education in the field of metal casting should be in line with the new developments in the industry. As the simulation tools increased and advanced, it became important to learn in conjunction with the practical experience, resulting in the minimization of the gap between the theoretical knowledge and practical experience [17]. This strategy safeguards the traditional skills and introduces the new technologies to improve the cast's productivity and quality. Moreover, digital twins can also be utilized to assess real-time casting conditions to enable the creation of a higher level of control over material properties and reduce defects as much as possible [18,19].

The other critical manufacturing process is welding, which is an important part of the automotive, construction, pipeline, and energy industries. There is also a shortage of skilled welders in the industry, which requires more effective training programs to be used [20]. TIG, which is of higher quality and has a versatile nature in terms of quality and usefulness, is extensively utilized in fabrication. TIG welding welds thick or thin plates; it, however, has demerits such as shallow penetration when used in a single pass. Heavier material involves multiple processes of filler metal, so increasing the cost of production and decreasing efficiency [21–23]. To improve the depth of penetration and to reduce the wastage of materials, several innovations have been made, including the active flux TIG (A-TIG) welding. Integration of AI-based welding robots, as well as augmented reality education modules, has significantly improved the accuracy and efficiency of welding processes [24–27].

3. Development of the metaverse for manufacturing

The integration of the Metaverse into the manufacturing sector is transforming the production, design, and efficiency processes by closing the gap between the physical and digital worlds. Real-time monitoring, modeling, and optimization using a digital twin enhances output as well as reduces perturbations [28]. Metaverse integration provides a tremendous enhancement to the product design process, as it allows working in a virtual space on a global team, allowing one to prototype right away, do iterative improvements and tests, reducing costs and accelerating development cycles. IoT data streaming provides real-time improvement of process monitoring, predictive maintenance, and optimization. The incorporation of the setup into the metaverse is a major advancement in enhancing the visualization, tracking, and accuracy of users in the process of metal casting [29]. In manufacturing processes, digital twins offer real-time modulization and optimization of rotation, pouring, and cooling of metal. This not only permits accurate control of rotating speed, mould-heat, and pouring dynamics, but also gets rid of the flaws and provides quality components.

Metaverse offers a secure learning platform to apply complicated casting procedures. The virtual training of mould preparation, molten metal handling, and fault diagnostics enhances competence and increases safety and process reliability [30]. IoT addition enhances the uses of casting with the aid of sensors to update the information about the state of the mould, metal flow, and the environmental conditions in real-time. This information is integrated with the Metaverse such that operators can monitor and control operations remotely [31]. Predictive analysis determines probable defects in advance before they take place, which always ensures the maintenance of quality and minimizes material wastage. Virtual casting processes allow manufacturers to investigate new designs and greener processes, layout optimizations, experiment with new alloy combinations, and save on energy use in a cost-efficient trial-free environment.

Amalgamation of the old art of production in recent years with new technologies, such as the Metaverse, enables the industry to modernize its practices, learn new expertise, and improve the quality of its products. The immersive environment can contribute to the promotion of innovation and technical progress in the production sector, providing the opportunity to simulate everything in real-time, optimize the process, and use immersive training spaces. In welding, the use of Metaverse-based VR simulations could allow operators to learn complex welding tasks, train, and examine the quality of welds in a safe virtual world. Data-driven interpretive feedback mechanisms help learners in understanding the influence of TIG welding parameters such as current, voltage, and gas flow on weld quality through real-time visualization and interaction. Combining an expertise that has been developed over time and cutting-edge digital capabilities will enable the manufacturing sector to achieve greater accuracy, safety, and sustainability in casting and welding, and be the next step in the history of smart manufacturing. The following sections illustrate the implementation of an immersive interacting environment for VCC and TIG, and how it has been used to couple virtual environments with real-world processes to achieve optimal training, monitoring, and process optimization.

4. Demonstration of an immersive interactive environment for VCC

Development of an immersive interactive environment for IoT-enabled VCC requires the creation of a virtual setup and its correspondence to the physical setup (**Figure 1**) in an integrated manner. These involve the selection of the hardware and software, the design of the DAQ and immersive VR world, engaging features, and extensive testing and experimentation. The integration fills the gap between the physical and virtual space that can be used to create an interactive and synchronized Metaverse of VCC.

Figure 1. Physical setup of VCC [11].

The strategy of this development involves multidisciplinary skills in 3D modeling, manufacturing procedures, DAQ, and software development. The arrangement of Vertical Centrifugal Casting (VCC) has been designed to suit molds of various sizes with varying aspect ratios. The system consists of a three-phase induction motor, which is then attached to a variable frequency drive, enabling rotational speeds to be between 25 and 200 revolutions per minute, which helps in the precise control of rotating the mold during the casting process. The molten metal in the VCC is poured through a specifically designed resistance heating bottom pouring furnace, where the metals can be melted and poured easily. A furnace can heat metal up to 1050 ℃ in 60 min, thus making it useful in casting processes. The bottom pouring mechanism enhances safety because one does not have direct contact with molten metal during pouring. A special stopper rod device is designed to make the task of pouring easy, which results in the accurate pouring of molten metal within the intended mold. After the metal has melted in the furnace, the stopper rod is then brought to a higher position, and the metal can flow, and then brought back to its position after the pouring has finished. The development of these systems is discussed in detail in another paper and not included here due to the brevity of space [11,32].

The integrated setup of VCC and Furnace with IoT features numerous sensors to monitor critical parameters such as atmospheric and molten metal temperature, humidity levels, air quality, and mold rotation speed. The sensors are connected to a cloud-based server through a microcontroller that sends the real-time data to a cloud server using the Message Queuing Telemetry Transport (MQTT) protocol. The system also incorporates relays to control the furnace and VCC functions, ensuring seamless operation in accordance with set standards. To integrate the IoT-enabled VCC with the metaverse, a virtual setup is created that replicates the physical setup. To create a 3D model of the VCC system with high precision and accuracy, CREO® is used, whereas Blender® is used for aesthetic reasons while rendering with details (**Figure 2**). A customized avatar was developed to make interactions possible inside the VR. These models are then imported into Unity Hub®, which is the most popular game engine, to give functionalities and responsiveness in real-time.

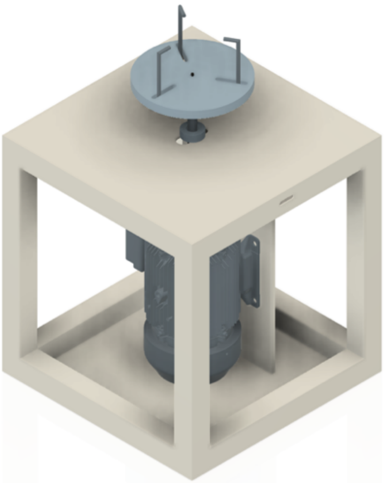


Figure 2. Rendered view of VCC [31].

The immersive environment is tested and validated using the VR headset, Oculus Quest 2.0, with sound to make the user experience intuitive. The whole VR system is connected to the cloud-based server, which enables real-time interaction with the physical VCC system. Through this integration, users would be able to monitor and control processes, such as mold rotation and molten metal pouring, through the immersive virtual interface. The rendered views of the VCC setup are shown in **Figure 2**, which gives a close-to-reality view of the physical setup.

The immersive environment in **Figure 3** shows a digital twin of the physical setup shown in **Figure 1**, allowing for an interactive virtual experience. A cloud-based server developed using C# and executed in Unity to enable the connection between the physical and virtual setups. **Figure 4** shows the interaction using a VR headset with a VCC setup. Along with monitoring and control over a process, the VCC environment based on the Metaverse allows making real-time changes and optimizing processes according to data analytics. The virtual environment enables users to see the flow stream, rotation, and solidification characteristics of metals, and predictive control plans can be applied. The environment provides interpretive defect-feedback based on process conditions, allowing learners to understand the relationship between parameter settings and defect tendencies.

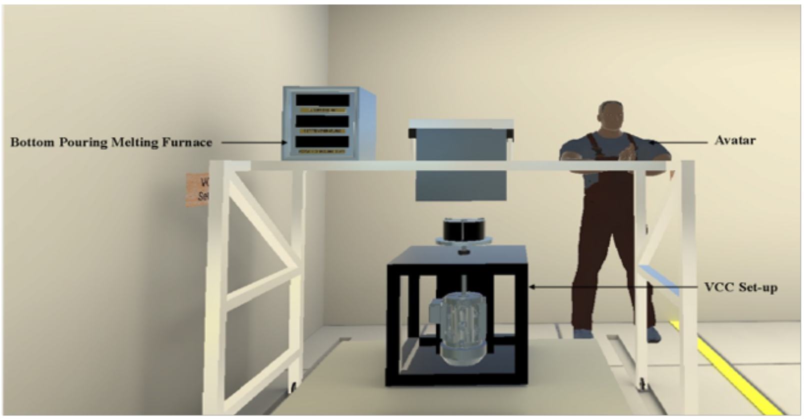
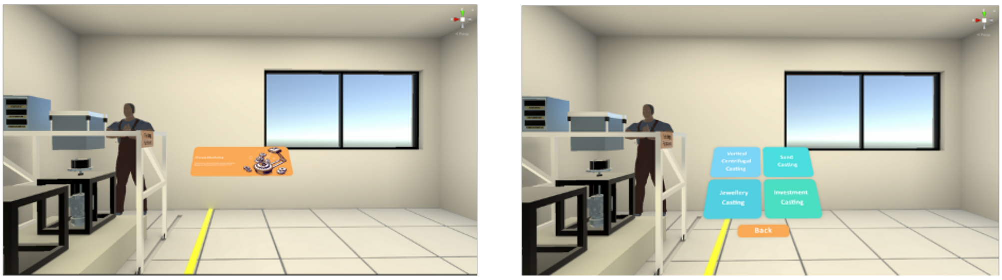
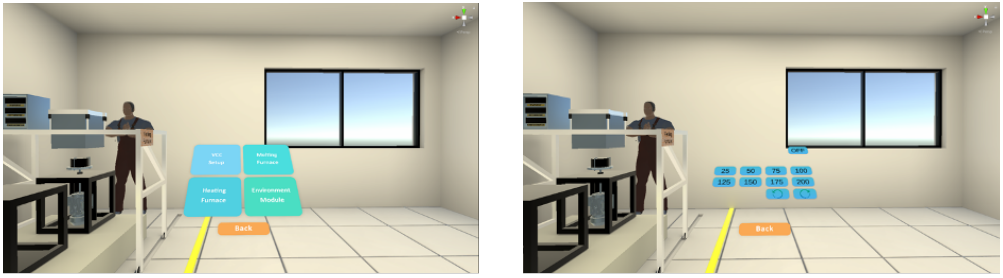


Figure 3. Immersive virtual environment for VCC and melting furnace [1].



(a) User interface.

(b) Different modules.



(c) Interaction with VCC.

(d) Tuning of the VCC setup.

Figure 4. The interaction process using a VR headset with a VCC setup.

For mechanical stability and safety, the developed VCC setup operates within a controlled environment where the rotation value ranges between 0 and 200 rpm.

Additionally, the VR training module offers interaction activities that allow a learner to have a practical experience in working with molten metal, mould preparation, and defect troubleshooting. The VR methodology consists of instructions, real-time performance testing, and feedback as a way of maximizing the learning results. Not only does this strategy improve the skill of the operator, but it also minimizes material loss and achieves process reliability. Haptic feedback also improves the experience by allowing the user to experience the weight and friction of working with the molten metal using VR controllers. This provides a training environment where the users can perform complicated operations in a safe environment before they perform them in a real-life environment. The Virtual Environment is also connected to a real-life environment where users are able to experience a simulated performance that includes actual manufacturing output, which will enable constant process improvement. This new-generation linkage can help manufacturers and training centres to simulate actual VCC processes, create a reduction in operation risk, and improve production efficiency. Simulation of virtual casting rooms, visualization, and interaction greatly improve decision-making capacity and precision of operation in the casting of metal.

5. Demonstration of an immersive interactive environment for TIG welding

The development of an immersive interactive environment for TIG welding necessitates the integration of physical and virtual environments and involves the choice of adequate hardware and software. The integration entails real-time data acquisition within the physical systems with the help of a Data Acquisition System (DAQ), an immersive environment, and interactive components to allow a synchronized virtual representation achievable with the assistance of sensors, communication protocols, and data processing and security technology.

This integration of technologies presupposes a multidisciplinary orientation and involvement of various areas of activity, including 3D modeling, DAQ, various types of welding processes, and software development. The first stage of development is to develop a physical platform that has integrated hardware (**Figure 5**). These aspects establish connectivity between the immersive interactive environment and the TIG welding system in real-time. A physical configuration of three-axis TIG welding is made by provisions of a stepper motor and ball screw to enable the movement of the torch in the three directions to result in increased accuracy, consistency, and efficiency in the welding work.

The physical set up of the welding that is developed (1—CNC Welding Machine, 2—Weld power Source, 3—IIoT Module, 4—Work Holding Table) is intertwined with the Data Acquisition System (DAQ) that monitors and controls the real time data of voltage, current and gas flow and precisely optimizes the process and stores it in cloud-based server to be further processed. Smart decision-making and optimization are based on the DAQ. With the physical infrastructure in place, Industrial IoT (IIoT) modules allow creating a smooth connection, processing data in real-time, and controlling it accurately. Sensors, such as current and gas flow sensors, collect the necessary data, actuators, such as stepper motor-controlled gas valves, provide perfect mechanical functionality, and Controllers, such as potentiometers, DC supplies, and microcontrollers, assist in managing the system and communication protocols to secure and reliable data transmission, transforming traditional systems into smart, connected industrial spaces in the metaverse.

Figure 5. Physical setup of TIG welding.
Note: 1—CNC Welding machine; 2—Weld power source; 3—IIoT module; 4—Work holding table.

The quality and accuracy of the welding is achieved by the actuators and controllers, which give the appropriate movement of the torch to make welds accurately, and the power source, which provides the required voltage and current, as well as the flow of the shielding gas, which is required to make the correct welds. To ensure effective management of the welding process, a robust database system is required to bridge the physical and digital environments. A performance-oriented NoSQL database is implemented to handle huge amounts of real-time data from the IIoT-enabled TIG welding setup. A scalable database allows smooth integration, storage, and processing of semi-structured and unstructured data. Through constant sensor data collection, the system provides real-time data to the metaverse for the accurate and interactive visualization of the TIG welding process.

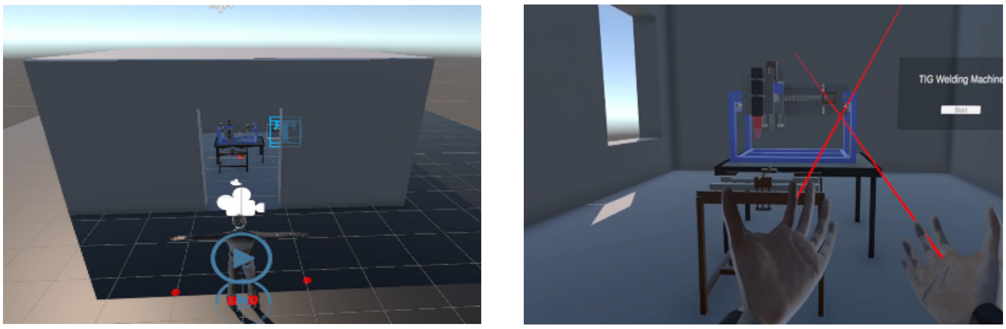
The next phase involves the development of a digital twin, a virtual replica of the TIG welding system. The development of a 3D model involves knowledge of detailed 3D modelling and rendering software, allowing users to visualize the process, track the system performance, and analyze potential issues beforehand. A 3D model of TIG welding is developed using advanced modelling software, CREO, whereas rendering has been done using BLENDER. Integration of the system helps in fetching real-time data from IoT sensors and controlling it in case of need, as well as simulating under various conditions and providing feedback for enhanced productivity, predictive maintenance, reduced operational cost, and improved efficiency. The setup of the TIG welding workstation is limited to a maximum current of 130 A to avoid any overheating of the torch assembly integrated with the sensors and to maintain safe laboratory operating limits.

In particular, up to the time-stamped TIG welding data like welding current, voltage, torch position, gas flow rate, and arc status, which are recorded when the experiment is running, are stored in the database and can be transferred to the digital twin in real-time to visualize the process variables (**Table 1**).

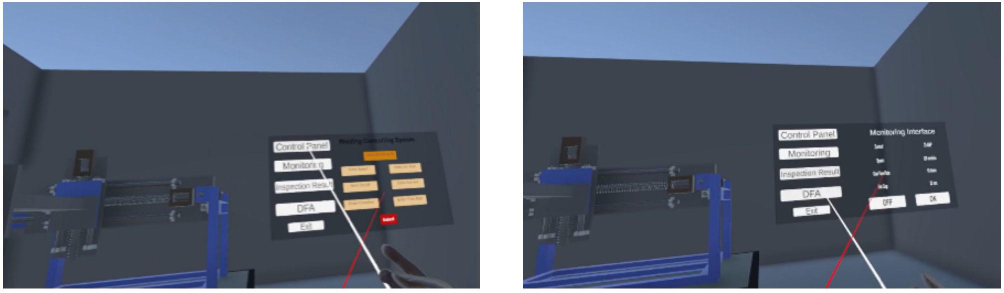
Table 1. Representative TIG welding parameters and observed weld characteristics.

Trial ID	Welding current (A)	Voltage (V)	Gas flow rate (L/min)	Travel speed	Observed weld characteristics
TIG-1	70	12	10	Slow	Narrow bead, shallow penetration
TIG-2	90	13	12	Moderate	Uniform bead, stable arc
TIG-3	110	13.5	14	Moderate	Improved penetration
TIG-4	130	14	15	Fast	Excessive heat input

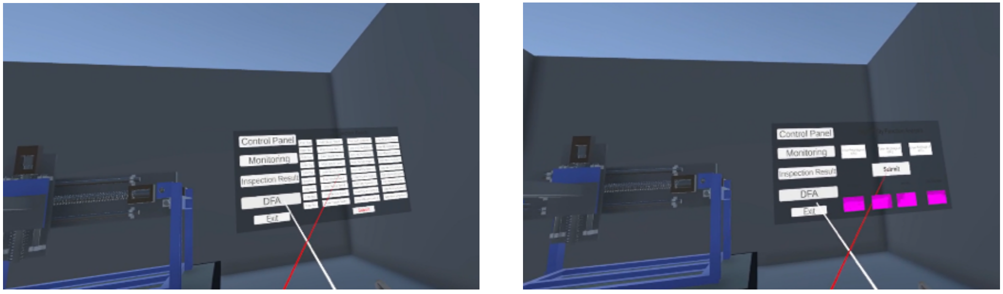
Once the digital twin is fully developed, it leads to the development of a metaverse environment. An immersive 3D environment is designed to simulate the TIG welding process for training and skill development using Unity HUB and C#. This virtual environment has highly detailed 3D models of all the related things for welding, such as welding tables, TIG welding machines, torches, workpieces, and safety equipment. A realistic visualization is created with advanced visual effects such as sparks, weld pool, smoke, heat distortion, dynamic lighting, etc., whereas spatial audio and haptic feedback add on to an immersive experience by providing sounds and vibrations (**Figure 6**).



(a) Virtual Welding Shop. **(b)** Dashboard.



(c) Control Panel. **(d)** Monitoring Dashboard.



(e) Inspection Dashboard. **(f)** Optimization using Design for Assembly (DFA).

Figure 6. Immersive virtual environment for TIG welding.

Real-time welding parameters such as current, voltage, travel speed, and gas flow rate are seamlessly collected using IoT sensors and integrated with a digital environment for smooth interaction, allowing the digital system to monitor and control real-time welding conditions in the metaverse. Along with the control and monitoring, the feedback system also plays an important role in enhancing the learning by demonstrating the effects of varying parameters on weld quality and heat distribution. The metaverse-enabled TIG welding environment offers multiple functionalities, including immersive learning through a VR interface that simulates the welding machine and workspace.

Learners can use any VR headset to experience and learning the TIG welding in an immersive environment. A popular VR headset, *Oculus Meta Quest-2*, is used for experimentation in this study, where controllers as well as hand tracking are used to input the welding parameters and simultaneously monitor real-time data. The functional panel is specially designed for control, monitoring, and inspection for process optimization, whereas the dashboard is utilized for tracking weld parameters and weld quality, assisted by data analysis tools to achieve refined welding parameters for enhanced efficiency and quality. A digital twin, along with the VR integration, enhances user familiarity with different welding components and provides better operational visualization in virtual space. Training on a virtual setup is a safe and cost-effective alternative for learners, reducing the challenges faced during working on a physical setup because of a hazardous environment and operating costs, providing a similar or better experience in a risk-free simulated environment. Virtual training is also useful in limiting wastage of material and safety issues, as well as offering real-time feedback to enhance skills development. Its other benefits include scalability, the ability to experiment with various parameters, and, at the same time, at no additional cost. Besides training, the metaverse also helps optimize the process and analyze defects that lead to the optimization of welding methods, which may promote better quality and performance of learners in their welding techniques, which is a bridge between traditional training and new and high-end digital welding technology.

6. Evaluation and system validation

In order to prove the efficiency and validity of the suggested metaverse-based learning in manufacturing education, a system-level and user-level assessment was conducted. The assessment has considered three major areas, which include (i) real-time system performance, (ii) digital twin synchronization accuracy, and (iii) user-centered learning and usability assessment (**Figure 7**).

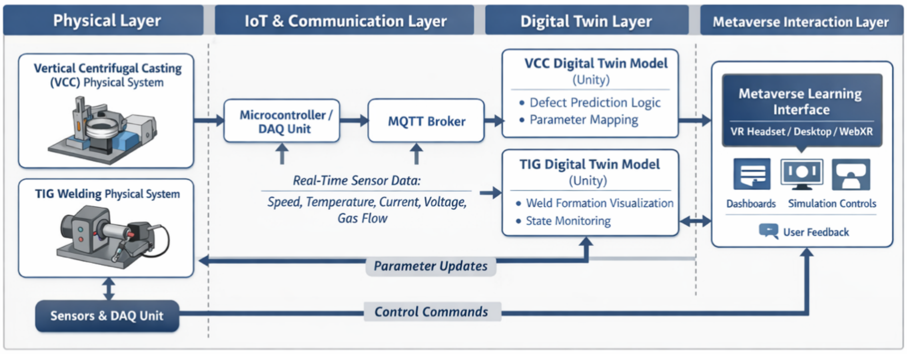


Figure 7. System architecture of the metaverse-enabled manufacturing framework.

6.1. System performance evaluation

The integrated physical-virtual system was tested in real time to ensure that there was a reliable interaction between the Vertical Centrifugal Casting (VCC) and the TIG welding stations with respective metaverse environments. The communication latency, frequency of data update, and stability of the system were used as key performance indicators.

Latency was evaluated qualitatively by observing the responsiveness of physical–virtual updates. It was also observed that the average end-to-end latency was acceptable to the real-time industrial training applications and thus allowed visualization to be smoothly achieved and user interactions to be responsive. The synchronization of data between the physical systems and their digital twins was consistent during a steady condition of operation, and no significant packet loss was observed during experimental sessions.

The communication architecture based on MQTT also proved to be effective in the transmission of data when operating in different conditions to validate the stability of the IoT-enabled system in the use of immersive manufacturing (**Table 2**).

Table 2. System behavior observed during experimental validation.

Parameter	Observation
Physical–virtual synchronization	Continuous and stable during operation
Response to parameter change	Immediate visual update observed
Communication stability	No interruption during experiments
User interaction	Smooth parameter tuning and feedback

6.2. Synchronization and functional validation of digital twin

The digital twins were functionally validated by comparing the performance of the physical systems to that of the virtual systems under varying parameter conditions. In the case of the VCC setup, mold rotation rate, pouring actions, and transformations of state in a process were observed in the physical as well as virtual world. On the same note, with respect to the TIG welding equipment, the welding current, voltage, gas flow rate, and the movement of the torch were assessed.

Changes in process parameters were also reflected in digital twins, which asserted the successful bidirectional synchronization. The flow representation of molten metal, rotational behavior, and welding dynamics showed consistent alignment with the state of the physical systems, thus showing the soundness of the digital twin models.

Representative experimental trials conducted on the Vertical Centrifugal Casting setup under varied operating conditions are summarized in **Table 3**, highlighting the relationship between process parameters and observed casting behavior.

6.3. IoT–DAQ architecture, communication, and safety validation

The Internet of Things (IoT) and Data Acquisition (DAQ) architecture was experimentally tested to ensure a reliable functioning of the framework and reproducibility of the entire vertically integrated manufacturing system through the physical operation of both the Vertical Centrifugal Casting (VCC) and TIG welding systems. The assurance was on data flow integrity, system controllability, and functional safety during an experimental state.

Table 3. Experimental Parameters and Outcomes for VCC Trials.

Trial ID	Mold rotation speed (rpm)	Pouring temperature (°C)	Mold preheat condition	Observed casting behaviour	Dominant defect tendency
VCC-1	25	700	Unheated	Incomplete metal spread	Misrun
VCC-2	50	725	Moderately preheated	Stable metal flow	Minor porosity
VCC-3	100	750	Moderately preheated	Uniform distribution	Negligible defects
VCC-4	125	775	Fully preheated	Improved densification	Reduced porosity
VCC-5	150	800	Fully preheated	Excessive centrifugal force	Surface segregation

6.4. IoT and DAQ system architecture

The physical manufacturing facilities were equipped by installing sensors with industrial-grade to measure important process variables such as the temperature, rotational speed, welding current, voltage, and the flow of shielding gases. These sensors were connected to a DAQ layer using microcontroller-based acquisition units, which provided the possibility of continuous acquisition of real-time data on the processes.

Data obtained was sent to a cloud-based server using Message Queuing Telemetry Transport (MQTT) protocol, which has been chosen due to its low latency, sparse architecture, and its ability to be reliable in the industrial Internet of Things application. The metaverse environment based on Unity subscribed to the corresponding data topics and allowed real-time visualization and interaction with the help of the digital twin. Authenticated control channels sent back control commands issued by the immersive interface to the physical system to allow bidirectional communication.

Such a modular structure has enabled the sensing, communication, and visualization layers to be independent and yet closely aligned to enable them to be scaled and adapted to other manufacturing processes.

6.5. Data validation

The IoT-DAQ pipeline was validated through functional validation in recurrent experimental operation. Real-time sensor data streams were uninterrupted and steady during live casting and welding experiments, and modifications at the physical layer were reflected in the virtual environment without any observable interruptions.

Control actions that were triggered by the interface of the metaverse, such as adjusting the rotation of the mold or the choice of the welding parameters, were carried out in a controlled form by the physical system, which proved the correctness of the command-response system. These experiments confirmed that the architecture can be used to provide stable monitoring and supervised interaction that can be used in education or demonstration purposes.

6.6. Security restrictions and access control

Since molten metal and welding arcs are involved and since such conditions pose serious threats to people, severe safety requirements were considered when designing the system. Interaction via the metaverse environment was only handled via controlled actions of supervision, and all significant safety decisions were kept at the physical system level.

The system incorporates:

- Emergency stop buttons in the physical installation.
- Fixed operational parameters of rotation speed, temperature, and welding parameters.
- Role-based access control means that only authorized users may start changing parameters.
- Learner training Simulation only modes, in which the physical actuation of the simulation is turned off.

In the process of experimental validation, any remote interaction was conducted in a controlled laboratory environment to prevent the immersive interaction from interfering with the safety of operators or equipment integrity.

6.7. Reproducibility and extensibility

The standard nature of communication protocols, modularity of hardware interface, and platform-neutral visualization tools all guarantee that the given framework can be replicated and expanded. The architecture is capable of being modified to support more manufacturing processes through changing sensor inputs, control logic, and digital twin models without changing the core system structure.

6.8. Learning and usability evaluation by the user

A pilot study involving a user-based analysis was carried out to determine whether the immersive environment was effective in manufacturing education. Undergraduate and postgraduate engineering students who had prior knowledge of manufacturing processes were taken as participants. The task was to make users complete some structured tasks in line with VCC operation and adjustment of TIG welding parameters in the immersive environment.

A pilot user study was also carried out in 15 learners who undertook predetermined casting and welding tasks in the immersive environment. The usability test was qualitative, based on structured observation, and the perception prompts were based on SUS without scores, because the study was exploratory. This pilot evaluation was aimed at checking the understanding of the tasks, the working system, and the educational quality of real-time feedback in the virtual environment.

The activity of learning was evaluated by the completion accuracy of tasks, time-to-completion, and the structured feedback after the session. A standardized System Usability Scale (SUS) questionnaire and subjective learning perception measurements were used to assess the usability.

The results of the evaluation showed:

- The usability scores are high and translate to an intuitive interaction and ease of navigation.
- Better, conceptual knowledge of process parameter relationships.

- Increased confidence of the learners in using manufacturing systems before touching them.

The participants noted the freedom to test process parameters safely, as well as to observe direct results, as one of the factors that contributed to better understanding and interest.

The experimental outcomes shown earlier (**Tables 1** and **3**) support these conclusions by connecting parameter adjustments with observed changes in casting and welding behavior.

6.9. Summary of evaluation outcomes

The system-level and user-level testing demonstrate that the suggested metaverse-based system offers:

- Fast and stable real-time communication between physical manufacturing systems and virtual worlds.
- Responsive and correct digital twin synchronization.
- Measurable changes in the level of engagement, comprehension, and perceived preparation of real-life manufacturing tasks in the learner.

These outcomes confirm the efficiency of the suggested solution as a scaled and secure platform for immersive manufacturing education that meets the Industry 4.0 demands.

7. Discussion

The results of the experimental validation (Section 6) support the fact that the developed metaverse-enabled framework not only allows the possibility to create an immersive visualization but also ensures a good level of synchronization between physical systems and digital twins. The regularity of the correspondence in the cases of VCC and TIG trials proves the stability of the operations necessary in the experiential learning and exploration of the processes.

The introduction of the metaverse in manufacturing education is a theoretical shift from the more traditional methods of teaching. The proposed system is based on experimental behavior in the real world, unlike the generic implementation of the metaverse. Additionally, the physical-virtual interaction that occurs when the trials are repeated ensures that the learners can have real manufacturing responses that reinforce conceptual knowledge and enhance the accuracy of the decision-making.

Metaverse helps fill the gap between theory and practice through the provision of virtual environments to simulate the actual process of manufacturing. As an example, AR and VR will provide the students with the opportunity to work with machines virtually, assemble components, and debug systems without necessarily being restricted by the physical nature of the workshops. This broadens access to quality education so that students with varied backgrounds develop skills that are relevant in the industry, regardless of their institutional resources.

These findings are consistent with the applied learning theory framework, in which principles of experiential and situated learning are advanced by real-time feedback, task-based interaction, and context-rich process behavior in the immersive setting.

The issue of manufacturing education safety is paramount. The conventional methods of learning usually require physical training on the dangerous materials and equipment, and as such, expose the learner to potential injuries and wastage of resources. Metaverse technologies reduce these risks because learners can learn in a virtual world, where the resources have no immediate effect on them. Process simulation, like metal casting or TIG welding, allows the students to make an error, correct it, and gain confidence without the impact on real life.

The exemplary results of the experiments in **Tables 1** and **3** are further evidence that learners can actively correlate process parameters with the apparent casting and welding results. This helps in the principles of experiential learning, as the principle allows repetitive trial-observation-reflection processes without wasting such materials or posing any safety threats.

The idea of the metaverse advances the advantage of immersive technologies by prompting the spread of collaboration across the world and the establishment of real-time communication. This is done by establishing decentralized virtual spaces where learners in various locations can work on projects together, exchange ideas, and participate in simulations in virtual factories. These environments further improve learning by experience and equip students with the dynamics of interdependence of modern manufacturing, such as the Industry 4.0 components of IoT-enabled systems, predictive maintenance, and digital twins.

The examples of the practical implementation of these technologies are virtual casting and welding simulations. Process simulators such as Vertical Centrifugal Casting (VCC) and TIG welding enable process learners to manipulate casting variables such as the rate of rotation of the mold, the pour temperature, and the heat input. These simulations also increase conceptual knowledge in addition to technical skills through imitating real-life conditions. As an example, students can investigate such defects as porosity in casting or optimization of weld penetration in TIG welding using controlled virtual experiments.

The development of digital twins in the metaverse is more of a transformative one. Digital twins allow combining real-time sensor data with virtual models to track processes with accuracy, predictively, and optimize them. This style is a way of introducing a gap between ancient craftsmanship and contemporary computing tools, a culture of innovation in the manufacturing practice. As an example, IoT-based systems offer real-time measurements on the conditions of the mould or the welding parameters that can be visualized in the metaverse to make real-time adjustments and prevent defects.

It is assumed that the impacts of these trends extend beyond the educational context to the training of the workforce and the work processes, where the metaverse would prepare the learners to face the growing complexity of the smart manufacturing systems, robotic automation, and sustainable practices. Additionally, the tools are effective in creating safety, efficiency, and cost-effectiveness in educational and professional settings.

Though quantitative performance metrics were not of interest in this study, the functional stability, responsiveness in real-time, and positive user interaction that were documented during the experimental sessions collectively confirm the suitability of the system in terms of training and early-stage deployment in education. Moreover, the immersive environment helps to achieve sustainability through a reduction in the number of materials wasted in the course of training, decreased energy consumption in relation to the repeated physical experiments, and the opportunity to learn in a safer way, directly influencing SDG 4 (Quality Education) and SDG 9 (Industry, Innovation and Infrastructure).

In conclusion, the integration of the metaverse into manufacturing education changes the process of knowledge and skills transfer. These tools not only accelerate the learning process but also guide the education practice to be able to address the demands of the digital, interconnected manufacturing reality. Through innovation and accessibility, immersive technologies are setting up a future-ready workforce, which can be used to propel the excellence of the new industrial sector.

Overall, the integration of the real-world experimental behavior, digital-twin visualization, and immersive interaction makes this system a validated and scalable solution to Industry 4.0-aligned manufacturing education.

8. Conclusion

This paper outlined the design and development, experimental execution, and functional validation of an immersive learning model powered by the metaverse to learn manufacturing that specifically covered Vertical Centrifugal Casting (VCC) and Tungsten Inert Gas (TIG) welding processes. The proposed system can be considered an effective way of bridging the gap between theoretical teaching and practice because it involves combining immersive virtual worlds with real physical manufacturing systems using IoT-enabled data-logging, digital twins, and interactive visualization.

The physical-virtual system was experimentally operated and confirmed to have stable levels of synchronization, reliable real-time interaction, and consistent correspondence between process parameter changes and observed system behavior. The test case experimental procedures prove that students can safely investigate the sensitivities of processes, the defect propensities, and operational limits in a controlled immersive space, therefore reducing the level of material waste and safety hazards.

Based on the learning theories that are already proven, such as experiential and situated learning, the suggested framework promotes iterative learning that relies on observation, interaction, and reflection. The combination of data-driven interpretive feedback mechanisms leads to improved process understanding that is achieved through contextual feedback in the case of immersive interaction, which strengthens cause-and-effect perception of complex manufacturing processes.

Altogether, the findings prove that the conceptualized metaverse platform is an experimentally validated, scalable, and extensible Industry 4.0-compatible manufacturing education platform. Although future research will emphasize the detailed quantitative learning tests and further coverage of the processes, the current research offers a solid experimental approach to immersive and dependent digital-twin-based training systems in the manufacturing of the advanced industry.

Author contributions: DA: Writing—original draft, methodology, software, and validation; AS: Supervision, writing—original draft, writing—review & editing, data curation, resources, validation, and project administration; MS: Writing—original draft, methodology, and software. All authors have read and agreed to the published version of the manuscript.

Funding: This work received no external funding.

Institutional review board statement: Not applicable.

Informed consent statement: Not applicable.

Data availability statement: The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to containing information that could compromise the privacy of research participants.

Conflict of interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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