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THE CONCEPT OF SMART INFORMATION SYSTEMS IN PRODUCTION ENGINEERING: A METAVERSE APPROACH

Nikola VITKOVIĆ¹, Miodrag MANIĆ¹, Milan MITKOVIĆ², Sven MARIČIĆ³, Marek CHODNICKI⁴,
George VOSNIAKOS⁵, Panorios BENARDOS⁵, Emmanuel STATHATOS⁵

Orcid: 0000-0001-6956-8540; Orcid: 0000-0002-7892-5957; Orcid: 0000-0001-6644-3216;

Orcid: 0000-0001-9471-5557; Orcid: 0000-0002-4484-8359

¹Faculty of Mechanical Engineering, University of Niš, Serbia

²Faculty of Medicine, University of Niš, Serbia

³Juraj Dobrila University of Pula, Croatia

⁴Gdańsk University of Technology, Poland

⁵National Technical University of Athens, Greece

*Corresponding author: nikola.vitkovic@masfak.ni.ac.rs

Abstract: The evolution of Industry 4.0 and Industry 5.0 has opened new pathways for integrating advanced digital ecosystems in production engineering. Among these, the Metaverse—a convergence of immersive XR technologies, real-time data, and collaborative virtual spaces—enables the development of Smart Information Systems (SIS) that enhance intelligence, adaptability, and interconnectivity. This paper explores how immersive, persistent digital layers support data-driven decision-making, digital twins, and human-machine interaction. By integrating XR, IoT, AI, and ERP systems, the Metaverse enables virtual prototyping, planning, and human-centered education. It also introduces an atomic knowledge approach, transforming tacit expertise into reusable, structured units embedded within SIS and Metaverse workflows. Technical architecture elements, including XR interfaces and cloud-edge integration, are outlined. Key challenges such as interoperability, privacy, latency, and scalability are addressed, alongside potential solutions and implementation pathways. This work proposes a foundational roadmap for resilient, human-centric, and intelligent production systems.

Keywords: Smart Information Systems, AI, ERP, Metaverse, XR, Virtual simulations, Workflow

1. INTRODUCTION

The rapid evolution of digital technologies is transforming production engineering through the integration of Smart Information Systems (SIS), which include artificial intelligence (AI), the Industrial Internet of Things (IIoT), cloud computing, and big data analytics. These systems enable intelligent automation and data-driven decision-making,

reshaping modern manufacturing. At the front of this change is the Industrial Metaverse, a virtual space where digital twins, extended reality (XR), cyber-physical systems, and human operators interact. This environment allows real-time engagement with digital representations of physical assets, facilitating

collaborative design, simulation, remote monitoring, and predictive maintenance.

The combination of SIS and the metaverse represents a shift toward more intuitive and intelligent production workflows. Integrating digital twins in immersive settings enhances situational awareness and enables virtual collaboration among geographically distributed teams. Nonetheless, challenges remain, including data interoperability, security, system scalability, and cognitive load. There is a need for effective frameworks to support real-world implementation. This paper explores how SIS can be embedded within metaverse architectures to advance production engineering. It offers an overview of enabling technologies, integration strategies, potential benefits, and the challenges ahead.

2. LITERATURE REVIEW

The transformation of production engineering through Smart Information Systems (SIS) is being accelerated by cyber-physical systems, the Industrial Internet of Things (IIoT), big data analytics, and artificial intelligence, hallmarks of Industry 4.0 and the emerging paradigm of Industry 5.0 [1, 2]. These SIS frameworks enable real-time monitoring, predictive maintenance, and adaptive decision-making in manufacturing environments. One of the key components of SIS is the digital twin (DT), which is a virtual replica of physical assets or systems that continuously mirrors real-time operational data. DTs enable simulation, optimization, and predictive control across the product lifecycle [3, 4]. While conventional DT implementations rely on 2D dashboards, recent advances are moving toward immersive representations using extended reality (XR) for more intuitive interaction and richer data engagement [5]. This evolution is converging into what is now termed the Industrial Metaverse: a persistent, shared digital environment where physical production systems, human operators, and digital twins co-exist and interact through immersive technologies [6, 7]. Leading

manufacturing enterprises like BMW and Siemens have demonstrated the potential of this approach, using metaverse platforms like NVIDIA Omniverse for virtual factory planning, simulation, and collaborative design [8]. Recent frameworks such as Digital Twin Systems Engineering (DTSE) seek to systematize the integration of digital twins, AI, and human-centered design within the industrial metaverse [3]. DTSE emphasizes not only real-time feedback and adaptive control but also the importance of ergonomic and cognitive interaction in production environments. In this context, human-centric digital twins (HCDTs) emerge as a critical direction, integrating physiological data, motion capture, and wearable sensor data to assess worker ergonomics, safety, and productivity [1]. Furthermore, integration of IoT infrastructure is essential for scalable and responsive metaverse deployment. Studies suggest that metaverse platforms built for industrial use, must satisfy core attributes including immersion, interoperability, scalability, and real-time responsiveness, while also addressing cybersecurity and data governance concerns [9]. Systematic reviews on digital twins and smart manufacturing identify key challenges such as data standardization, model fidelity, real-time synchronization, and the need for robust simulation capabilities [4, 10]. Other studies emphasize that while individual components of the industrial metaverse such as XR training tools, AI-based predictive systems, and cloud-edge computing, are maturing, comprehensive integration into unified platforms remains limited [6, 7].

In summary, the current research establishes a strong foundation for SIS, digital twins, and immersive technologies as enablers of next-generation production systems. The Industrial Metaverse builds upon these pillars by offering a unified virtual-physical space for intelligent, human-in-the-loop manufacturing. However, further work is needed to develop interoperable architectures, standard protocols, and validated frameworks to fully realize this vision in industrial settings.

3. METHODOLOGY

This paper applies a conceptual and scenario-based methodology to demonstrate how atomic learning and immersive technologies can be integrated into Smart Information Systems (SIS) for production engineering. The approach is centered on modeling a real-world medical use case, specifically, the customization of internal plates and fixators, through the E-COOL platform and Metaverse-supported collaboration. A Workflow process model is used to map the interaction between physicians, engineers, and designers, highlighting how knowledge atoms are created, shared, and refined during design and manufacturing. The methodology focuses on the alignment of XR simulation environments with SIS logic, enabling the transformation of tacit and explicit knowledge into interoperable digital workflows. The proposed framework is evaluated through its ability to support personalized implant production while promoting collaborative decision-making in line with Industry 5.0 goals.

3.1 The Metaverse as a “Second World” Enabled by XR Technologies

The Metaverse can be understood as a persistent, immersive, and interactive “second world”, an alternate digital layer that mirrors and extends the physical realm, where users, digital twins, and systems coexist in real time. This ecosystem enables realistic interactions with virtual assets that go beyond traditional representations, offering enhanced collaboration and simulation in shared virtual environments. At the core of this second world lies Extended Reality (XR), a combined term for immersive technologies including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). XR transforms flat dashboards into spatial, interactive environments: VR fully immerses the user in a synthetic space; AR overlays digital data on the real world; MR blends real and virtual objects in seamless coexistence. These

modalities allow operators and engineers to engage intuitively with digital twins of production systems, supporting tasks such as training, remote diagnostics, virtual commissioning, and collaborative design. In industrial settings, XR-powered Metaverse spaces allow users to inhabit and manipulate live operational models, navigating through digital factories, simulating process flows, and diagnosing equipment performance virtually. These capabilities enable remote collaboration and real-time feedback, facilitating rapid response to disruptions and process variation. Recent studies highlight that XR in manufacturing enhances situational awareness, improves cognitive load management, and supports human-centric design principles by embedding users within the virtual production context [11]. Additionally, XR interfaces foster embodied interaction with digital twins, enabling spatial reasoning and shared decision-making among distributed teams [12]. By embedding SIS, AI analytics, and XR within the Metaverse, production engineering enters a new era of human-in-the-loop, immersive manufacturing systems. Rather than simply mirroring reality, this second world redefines the way data, systems, and people interact, spatially, continuously, and intuitively, in the spirit of Industry 5.0.

3.2 Manufacturing Workflows in Production Engineering

Manufacturing workflows denote the structured processes that convert raw materials into finished products. These workflows encompass design, prototyping, planning, production, maintenance, quality control, and logistics, coordinated across machines, systems, and human operators. In advanced production engineering, workflows have evolved into dynamic, data-driven, and adaptive sequences, enabled by Smart Information Systems (SIS) such as MES, ERP, AI analytics, IIoT sensors, and digital twins. Through these SIS integrations, production workflows now support real-time monitoring,

predictive maintenance, adaptive scheduling, and just-in-time manufacturing, minimizing downtime and enhancing efficiency. However, managing and visualizing these complex processes remains challenging due to the volume and heterogeneity of data, and the limitations of traditional 2D dashboards in conveying high-dimensional operational insights. To address these challenges, Extended Reality (XR) technologies are being integrated with digital twins to create immersive workflow experiences. XR-powered digital twins bring workflows into spatial contexts, allowing users to walk through factory layouts virtually, simulate assembly lines, and observe material flows in a single interactive environment [13]. For example, XR visual guidance in virtual assembly experiments has demonstrated over 50% reduction in task completion time and errors, underscoring XR's potential to enhance efficiency and reduce cognitive load [14]. By embedding manufacturing workflows within immersive XR environments, operators and engineers gain situational awareness, spatial reasoning, and real-time interaction with process data. This leads to more intuitive control interfaces, proactive decision-making, and collaborative optimization across teams, especially suited for Industry 5.0's human-centered production paradigms.

3.3 Metaverse Integration in Manufacturing Workflows

Integrating the Industrial Metaverse into manufacturing workflows fundamentally reimagines traditional production with immersive, real-time, and spatially rich environments. This integration is achieved by layering Smart Information Systems (SIS), including digital twins, AI analytics, IoT data, and XR interfaces, onto each operational phase. In design and process planning, engineers engage with a virtual 3D twin of the factory using VR to explore facility layouts, simulate production sequences, and test configuration scenarios. This immersive planning can accelerate decision-making,

prevent costly rework, and optimize material utilization [15]. During production operations, the metaverse supports augmented reality (AR) interfaces for shop-floor personnel, delivering contextual overlays such as machine health metrics, task instructions, and safety warnings directly in the worker's field of view. This contextual layer boosts accuracy, reduces training time, and enhances situational awareness. For maintenance and quality assurance, mixed reality (MR) environments allow technicians and remote experts to interact with digital twins of equipment in real time. Stakeholders can diagnose faults, annotate repairs, and validate outcomes collaboratively in the same immersive virtual space, minimizing downtime and extending asset life [16]. Moreover, training and workforce development have been transformed. XR-enabled immersive simulations recreate real-world scenarios, transecting physical boundaries and enabling remote teams to train, collaborate, and innovate as avatars in a unified digital environment. A layered architecture model supports these integrations: real-time IoT telemetry feeds into a metaverse engine, which renders spatially coherent digital twins accessible via XR devices. Human operators (Meta-Operators) interface with this platform for seamless interaction across design, production, and maintenance phases [2].

These immersive integrations position the metaverse as more than a monitoring tool, yet it becomes an active, human-centered control layer overlaying physical workflows with spatial insight, collaboration, and intuitive decision support. Integrating SIS, XR, and immersive metaverse spaces thus offers a new paradigm for adaptive, efficient, and sustainable production systems in the era of Industry 5.0.

3.4 Enabling Tacit Knowledge in the Metaverse

Traditionally, tacit knowledge, the unspoken, experience-based know-how held

by skilled workers has been difficult to digitalize or transfer. The Metaverse, however, offers new opportunities to externalize and simulate this type of knowledge through immersive technologies. By capturing expert behaviors using motion tracking, gesture recording, and contextual voice interaction in XR environments, the Metaverse enables the encoding of skilled actions and decision-making processes. These recorded sessions can be replayed, adapted, and embedded in training scenarios or simulation workflows, allowing others to learn by virtually observing or interacting with expert avatars in situ. This approach facilitates not only knowledge retention as senior workers retire, but also knowledge scaling, as expertise can be delivered remotely and repeatedly. Furthermore, designers and engineers can embed tacit insights into virtual prototypes or collaborative spaces, enabling richer interdisciplinary co-creation. Thus, the Metaverse becomes a living knowledge environment, not only hosting data and processes but preserving and transmitting human skill, bridging the gap between explicit data and human intuition in production engineering.

3.5 The Atomic knowledge addition to Industrial SIS and Metaverse

Atomic knowledge refers to small, self-contained units of domain-specific expertise that can be modularly applied, reused, and shared across smart manufacturing systems. When integrated into Industrial Smart Information Systems (SIS) and the Industrial Metaverse, atomic knowledge serves as a dynamic bridge between data-driven automation and human-centric intelligence.

In traditional SIS, decision-making often relies on large data models or static expert rules. Atomic knowledge introduces small, adaptable knowledge artifacts, for example, how a specific implant geometry affects load distribution or how a material behaves under heat treatment. These atoms can be triggered by context (e.g., a CAD model, sensor reading,

or user input) and embedded within digital twins, simulation environments, or XR interfaces in the Metaverse.

By incorporating atomic knowledge, the Metaverse becomes more than a visualization space. It evolves into an interactive learning environment, where engineers, physicians, and designers can retrieve, contribute, and validate domain insights in real time. These atoms also enable knowledge versioning, traceability, and AI-supported recommendation, essential for continuous improvement in complex manufacturing ecosystems. Thus, atomic knowledge enhances the adaptability, reusability, and personalization of SIS and XR workflows, empowering human-machine collaboration at the heart of Industry 5.0. The one approach for integration of novel atomic knowledge into existing educational material is presented in Figure 1.

This diagram illustrates a structured workflow for transforming initial educational materials into modular, atom-based course content. The process begins with the Material Analysis, conducted by educators (M1), to identify the fields and topics present in the input material. Based on the NEM definition (C1), the content is then organized in the Material Separation into Sections phase. This step uses domain-specific criteria such as science fields and topic aggregation methods to logically segment the material. Next, the Feature Extraction and Atom Definition stage identifies minimal learning units, termed "atoms", along with their representations and interrelations. This step is crucial for enabling personalized and adaptive learning structures. Supporting references guide the definition and representation of these atoms. In the final phase, Formation of the Courses, atoms are assembled into coherent course structures, guided by Novel Educational Methodology (NEM) [17] (C2) and informed by student needs (M2). The output is a logically structured, atomized curriculum that supports microlearning and facilitates flexible educational delivery. The framework enables a precise breakdown of complex educational

content into granular, reusable learning units, making it suitable for intelligent tutoring systems, e-learning platforms, and personalized learning environments. It reflects modern educational paradigms aligned with digital transformation and adaptive instruction.

To demonstrate the application of atomic learning within Smart Information Systems (SIS) and the Metaverse, the following medical use case is presented (Figure 2) and analysed.

This diagram extends the concept of atomic learning to the domain of biomedical product development and surgical planning. It outlines a workflow from Product Design to Simulations, including Material definition. These elements represent modular topics that can be taught, assessed, and reused independently.

They can be created, modified and reused by different skilled groups, like professors, engineers, scientist, and other which are interested in specific topic.

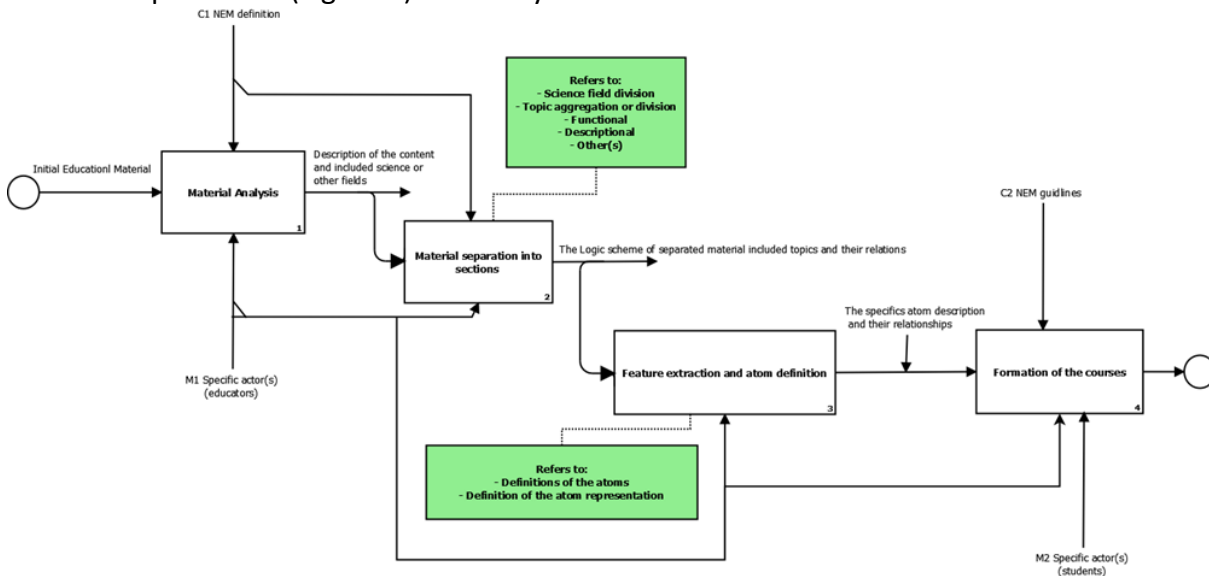


Figure 1. The SADT diagram for improvement of educational material by using atoms of knowledge

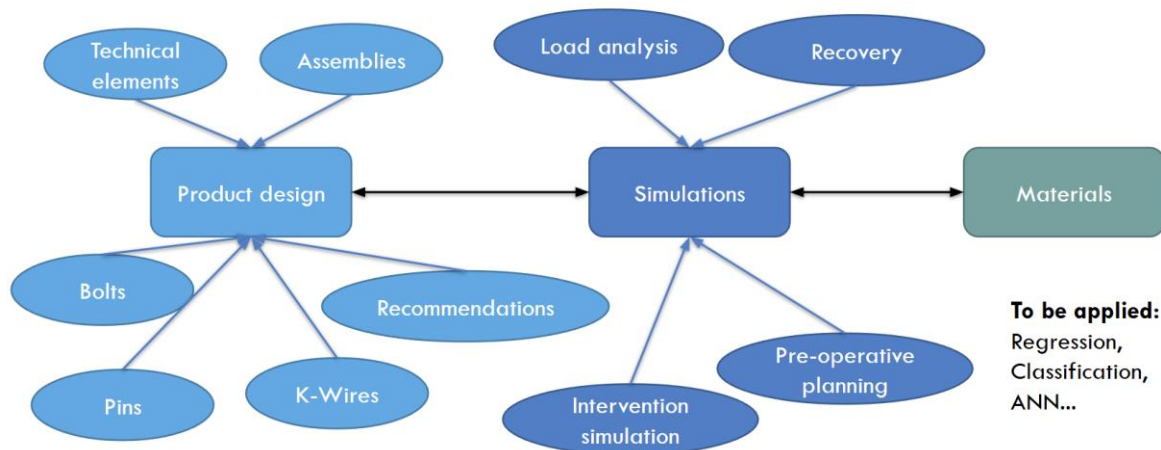


Figure 2. The Conceptual representation of the medical atoms in the specific domainsIn the

Simulation phase, atomic knowledge extends to Load Analysis, Recovery, Recommendations, Intervention Simulation, and Pre-operative Planning. Each simulation topic forms an atom that can be aligned with targeted educational objectives. For instance,

one atom might focus on simulating the mechanical response of K-wires under stress, while another focuses on the recovery processes. The inclusion of AI techniques, such as regression, classification, and artificial neural networks (ANNs), highlights the potential for

intelligent tutoring systems to personalize content delivery and evaluation. These models can adapt learning paths based on individual performance or decision-making behavior in simulations. Overall, atomic learning enables a personalized, modular, and adaptive training approach that bridges engineering design and clinical applications, promoting effective learning in interdisciplinary medical education environments. To demonstrate the application of the aforementioned technologies, the following section presents a use case (Figure 3) on personalized implant production.

3.6 The personalised implant production proces

This diagram illustrates a comprehensive workflow for applying atomic learning and XR-based knowledge delivery in the development of personalized implants. The process begins with Patient Diagnostics and continues through the detection of the problem, leading to a need for a personalized implant.

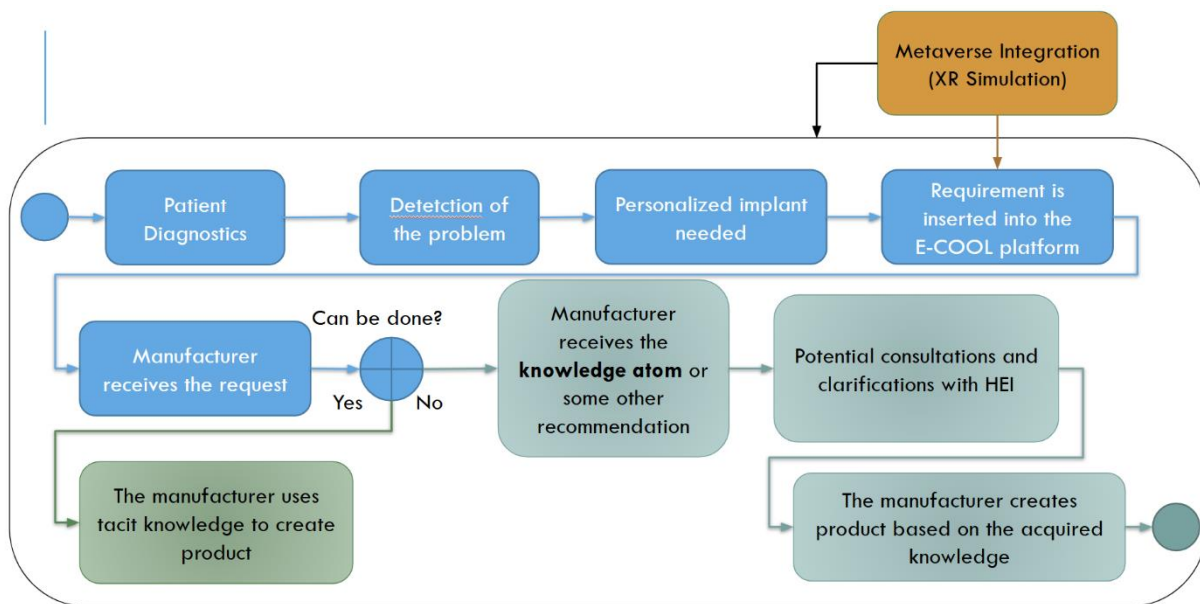


Figure 3. Comprehensive workflow for applying atomic learning and XR-based knowledge delivery in the development of personalized implants

The manufacturer receives the request, and the system checks whether the task can be fulfilled. If feasible, the manufacturer proceeds using tacit knowledge, practical, experience-based insights, to create the product. Alternatively, if additional information is needed, the manufacturer receives a knowledge atom or a structured recommendation. These atoms, representing minimal and reusable learning units, are informed by simulations and previous expert experience. To enable more visual approach, the integration of Metaverse (XR Simulation) is included. It supports immersive visualization, planning, and communication, enabling more informed decisions. If uncertainties remain, consultations with Higher Education Institutions (HEIs) help clarify the meaning or

content of the knowledge atom. Ultimately, the manufacturer creates the product based on the acquired explicit or tacit knowledge. This workflow exemplifies how atomic learning, enhanced with XR and collaborative platforms, can enable responsive, knowledge-driven manufacturing tailored to individual medical needs, bridging diagnostics, design, education, and production in an intelligent healthcare ecosystem. The Workflow Swimline diagram, which describes the presented process, is shown in Figure 4.

This workflow diagram outlines a collaborative workflow among physicians, engineers, and designers in the development of personalized implants, leveraging both the E-COOL platform and Metaverse (XR Simulation) integration. The process starts in the Physician

lane, where a patient undergoes diagnostics. Upon detection of a problem, a personalized implant is identified as necessary and entered into the E-COOL platform. The process transitions to the Engineer, who receives the request and evaluates its feasibility through a decision node: “Can be produced?” If the

answer is yes, the process continues using existing tacit knowledge. If not, the engineer accesses a knowledge atom or consults with higher education institutions (HEIs) for clarification. These consultations are essential for further improvement of the process of creating different products.

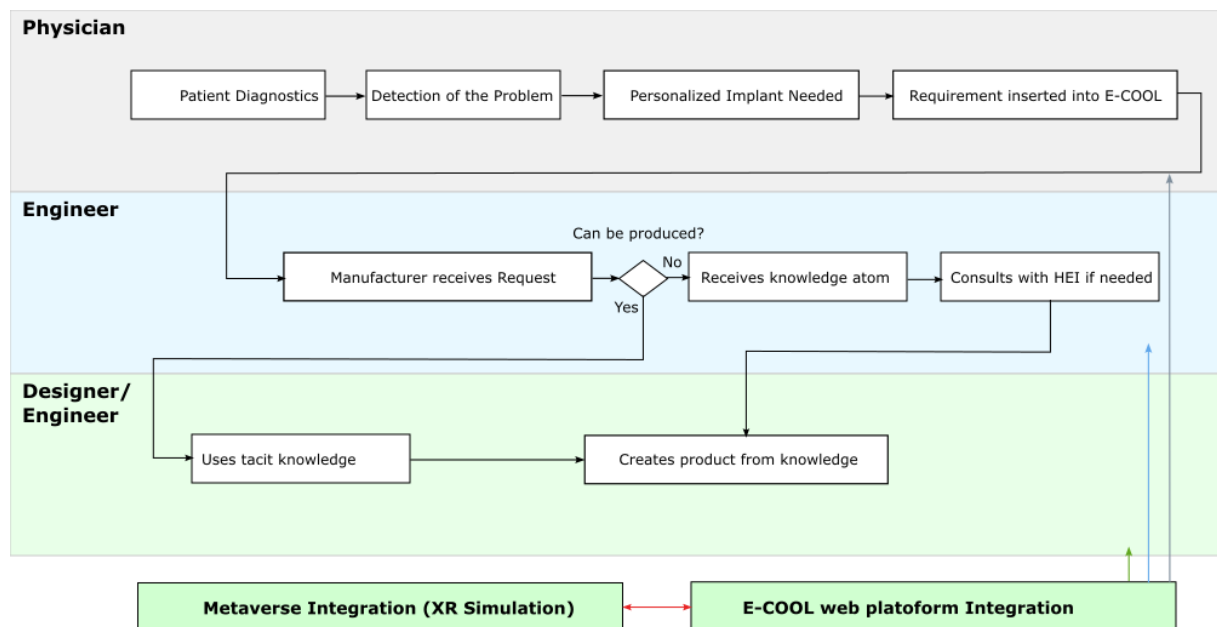


Figure 4. Comprehensive workflow for applying atomic learning and XR-based knowledge delivery in the development of personalized implants

In the Designer/Engineer lane, tacit knowledge and recommendations, obtained through XR simulation or expert consultation, are used to guide the design and manufacturing of the personalized product. The designer ultimately creates the product based on this accumulated knowledge. At the bottom, the Metaverse Integration (XR Simulation) and E-COOL platform serve as enabling infrastructures. XR provides immersive training, testing, and decision support, while E-COOL ensures traceability and centralized data handling. This framework enables efficient collaboration and knowledge transfer between disciplines, promoting precision, personalization, and intelligent manufacturing in healthcare innovation.

3.7 Example Scenario: Custom implant development using the Mitković-type internal fixator

In cases of complex tibial plateau fractures, presented in Figure 5, particularly those with unusual bone morphology, prior surgical alterations, or asymmetrical deformities, the standard Mitković internal fixator may require customization. Consider a patient with a severe lateral tibial plateau fracture and preexisting skeletal irregularities due to previous trauma. In this case, the orthopedic surgeon, following radiographic diagnostics and 3D CT reconstruction, determines that a standard fixator does not fit the lateral contour properly, risking improper stabilization and delayed healing.

Using the E-COOL platform, the physician initiates a request for a custom variant of the Mitković internal fixator. The request is reviewed by the engineering team, who perform feasibility analysis using digital twin simulations and finite element validation. If uncertainties arise regarding stress distribution or anatomical fit, the case is transferred to the

Metaverse platform, enabling immersive collaboration between the physician, engineers, and implant designers. Within this XR environment, they visualize the patient-specific anatomy, manipulate a 3D model of the fixator in real scale, and simulate the surgical procedure virtually. Using prior implant knowledge as well as new insights gathered during simulation, the system generates a refined “knowledge atom” to support the redesign. The design team applies reverse engineering on existing Mitković components,

adapting the geometry to the patient’s anatomy using CAD/CAM integration. Final prototypes are validated in the Metaverse environment before production. The output is a custom-fabricated, patient-specific internal fixator that conforms to Mitković’s biomechanical principles while adapting to anatomical constraints, and is delivered with greater precision, collaboration, and reduced turnaround time.

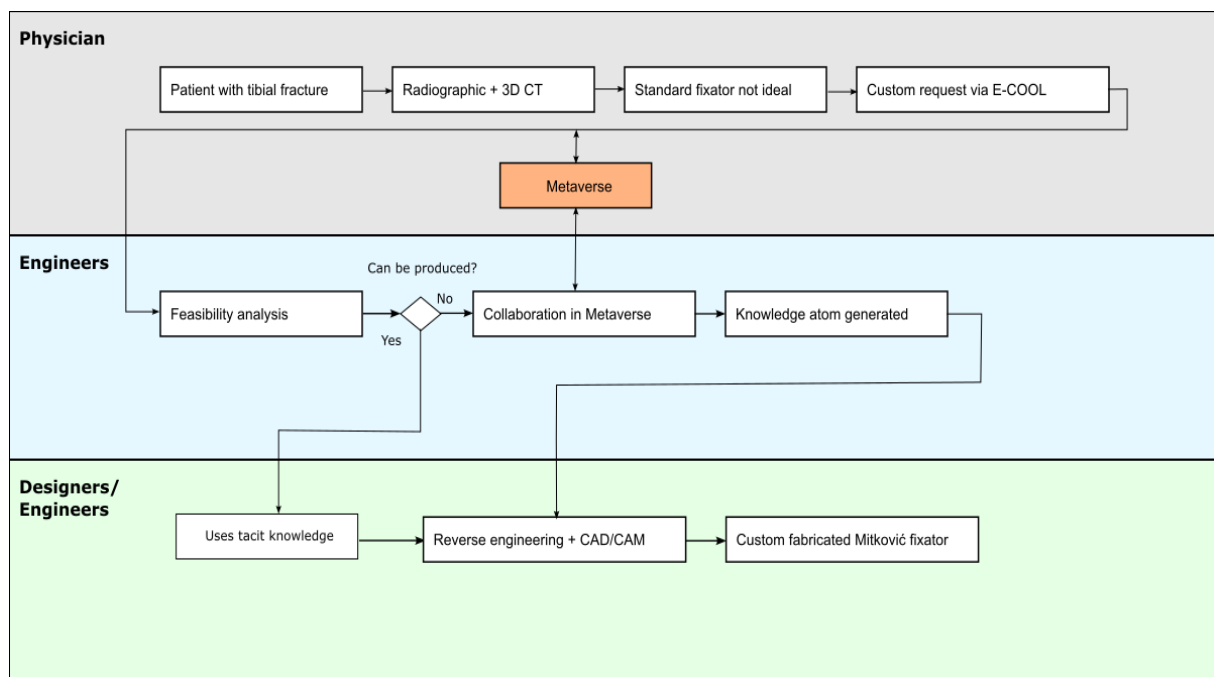


Figure 5. Workflow for Metaverse application in producing customized Mitkovic type internal fixators

4. CONCLUSION

This paper proposed a novel integration of Smart Information Systems (SIS), atomic learning, and Metaverse technologies to support collaborative, knowledge-driven production engineering. By conceptualizing the Metaverse as a shared digital environment, the framework enables engineers, designers, and physicians to interact in real time, simulate workflows, and contribute to a dynamic repository of atomic knowledge. The personalized implant use case, based on Mitković-type internal fixators, demonstrates how immersive technologies and modular knowledge units can transform traditional design and manufacturing processes.

Knowledge atoms, generated during simulation and decision-making, enhance the system’s adaptability and reusability across similar scenarios. This approach supports Industry 5.0 goals by aligning human expertise with digital intelligence and immersive collaboration. Future work will involve the formal structuring of atomic knowledge and practical validation across various domains. The proposed methodology represents a scalable foundation for building intelligent, human-centered production systems enhanced by extended reality and smart data integration. The possible applications are only limited by human imagination.

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