Multimodal Technologies and Interaction

MDPI

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Physics-Based Tool Usage Simulations in VR

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Abstract: The need for scalable, immersive training systems is universal and recently has been included in fields that rely on complex, hands-on processes, such as surgery operations, assembly operations, construction processes training, etc. This paper examines the potential to support immersive training via digital tool manipulation in the domain of traditional handicrafts. The proposed methodology employs Finite Element Method simulations to compute material transformations and apply them to interactive virtual environments. The challenge is to accurately simulate human–tool interactions, which are critical to the acquisition of manual skills. Using Simulia Abaqus (v.2023HF2), crafting simulations are authored, executed, and exported as animation sequences. These are further refined in Blender (v3.6) and integrated into Unity to create reusable training components called Action Animators. Two software applications—Craft Studio (v1.0) and Apprentice Studio (v1.0)—are designed and implemented to enable instructors to create training lessons and students to practice and get evaluated in virtual environments. The methodology has wide-ranging applications beyond crafts, offering a solution for immersive training in skill-based activities. The validation and evaluation of the proposed approach suggest that it can significantly improve training effectiveness, scalability, and accessibility across various industries.

Keywords: vocational training; physics-based simulations; finite element method; process simulation; virtual reality

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Academic Editor: Julius Nganji

Received: 6 February 2025
Revised: 11 March 2025
Accepted: 19 March 2025
Published: 24 March 2025

Citation: Partarakis, N.; Zabulis, X.; Zourarakis, D.; Demeridou, I.; Moreno, I.; Dubois, A.; Nikolaou, N.; Fallahian, P.; Arnaud, D.; Crescenzo, N.; et al. Physics-Based Tool Usage Simulations in VR. *Multimodal Technol. Interact.* **2025**, *9*, 29. https://doi.org/10.3390/mti9040029

1. Introduction

Immersive training systems respond to the need for efficient and scalable vocational training systems in skill-intensive domains [1]. Professions that require the acquisition of knowledge of manual procedures such as craft-based industries, assembly lines, and factories are well-suited for immersive training because they rely heavily on hands-on experiences and the mastering of complex physical interactions [2]. For example, Virtual Reality (VR) in training can provide hands-on experiences and simulate complex physical interactions [3]. The scalability and accessibility of VR-based training systems have also been studied, supporting the argument that immersive systems can provide flexible and accessible training solutions [4]. On the efficiency of these learning approaches, a review of research in this domain has shown that Augmented Reality (AR) and VR can enhance learning by providing immersive, interactive experiences, which is particularly relevant for preserving procedural knowledge [5].

Traditional methods of instruction in these professions currently involve mainly in-person mentoring [6]. Except for common practice, the importance of mentoring and hands-on learning in vocational training is also a research finding when studying such contexts [7]. At the same time, traditional methods rely on the existence of practitioners to provide their expertise and know-how [8]. In the case of Traditional Crafts (TCs), where the population of practitioners is declining, gestural and procedural knowledge should be urgently preserved [9]. UNESCO highlights the global decline in TCs as part of Intangible Cultural Heritage (ICH), emphasizing the urgent need to preserve these skills and knowledge systems [10]. The challenges posed by the declining number of practitioners is far more important in apprenticeship-based training systems [11]. Understanding and preserving such knowledge can support the creation of immersive systems and thus provide flexible and accessible training.

The core challenge in this work is to provide an accurate representation of craft actions in immersive training environments. To do so requires understanding processes and being able to accurately simulate the real-world behaviors of tools, materials, and human actions. In this work, we build upon previous efforts on the representation of crafts [12] and we enrich them by moving a step further into providing scientifically simulated occurrences of the documented processes. We employ scientific simulation to acquire data and thus support realistic training in crafting activities.

Our approach is rooted in the Finite Element Method (FEM) simulation which has been extensively used in engineering and material sciences. Currently, the application of the FEM to human activity simulation is an emerging field. The FEM is of particular interest in the studied domain since it provides high-fidelity simulations of how materials respond to forces, stresses, and deformations which is a prerequisite for simulating traditional crafts where the interaction of the human with the material through the skillful usage of tools is of the essence. Current research in immersive training is advancing, without considering the potential of FEM integration. Thus, these systems are still using “fake reality” simulations, particularly when it comes to real-time interactions. The works in this area [13–15] have demonstrated the effectiveness of the FEM in modeling physical phenomena, but its application to training human activities is a relatively new exploration. In this domain, the application of the FEM is currently studied for medical surgery training [16,17].

Furthermore, there are competing views on the simulation of human actions in virtual environments. Some works are in favor of physics-based simulations that rely on computational models to calculate the outcomes of actions based on physical laws [18–22]. Other words are in favor of evidence-based practice which is considered a prerequisite of realism [23–27]. In the first case, the computer is calculating the results of an action through physics simulation. In the second case, animations are generated by monitoring real actions or simulating them. Other works propose a combination of the above methods [28–30]. In this work, we are using physics-based simulations in conjunction with data-driven methods and game engine-based rendering.

To address the aforementioned gaps, this work is proposing a methodology for immersive training that integrates the FEM with virtual environments, animations, and interactive software solutions. This approach not only enables the precise simulation of crafting actions but also ensures that the system is adaptable and reusable across different scenarios. The methodology includes the use of Simulia Abaqus [31] to simulate crafting processes, a custom script to export animation sequences, and integration with game engines such as Unity3D [32] to deliver a fully interactive training experience.

Furthermore, to deliver these technologies as immersive experiences, this work presents the design and implementation of two software applications Craft Studio and Apprentice Studio which serve as the instructor and learner interfaces, respectively. Craft Studio supports the creation of detailed lessons, combining physics-driven simulations with immersive environments that utilize both traditional and advanced input/output devices, such as VR controllers and haptic feedback systems. Apprentice Studio supports the execution and monitoring of training activities in a highly realistic virtual environment.

2. Background and Related Work

This section summarizes related work focusing on VR, AR, and physics-based simulations. It also explores serious games in providing interactive and engaging training experiences. Additionally, the section highlights the potential of FEM simulations in human activity simulation and their application in immersive training environments. Finally, it discusses the creation of realistic and effective virtual training systems, emphasizing the importance of the accurate replication of real-world conditions and the integration of haptic feedback to the training experience.

2.1. Current State of the Art in Immersive Training

Immersive education and training have evolved due to new technologies such as VR [33] and AR [34]. These technologies have supported the development of virtual environments to simulate real-world spaces [35] including heritage spaces [36,37]. Several software platforms have been developed to support this type of immersive learning, enhancing traditional training approaches [38,39]. Furthermore, modular systems that integrate animations of human activities as components [40,41] can support the creation of training programs by combining different animations into structured lessons [42,43]. In such systems, VR headsets and haptic devices can provide both visual and tactile feedback, making the training experience more realistic [44–46]. Such systems enable users to practice in virtual workshops [47] with prior works assisting, for example, ceramic design [48], wood assembly [49], and woodworking tools simulation [50].

The potential for virtual training environments to replicate real-world conditions is demonstrated in several studies [51,52]. Such systems are becoming more adaptable, supporting various input methods (e.g., VR controllers and haptic feedback devices), overall enhancing interaction and experience.

2.1.1. Game-Based Training

Computer games have supported creative interaction with the virtual environment and in some cases even replicating basic crafting aspects. For example, pottery simulation is found in several games engaging creativity (e.g., 3D Pottery [53], Pottery Master [54], and Pottery Simulator [55]), albeit not exhibiting high levels of realism, nor addressing practical constraints. In the adventure game genre [56], the prerequisite of crafting or recipe materials is addressed by requiring them to be available for the execution of an action. This is also the case for alchemy systems used in some role-playing games [57].

The Knitting Simulator 2014 [58] requires handling the VR controllers as knits. In [59], the same metaphor is used to edit solids by revolution in lathe crafting. A solution for generic crafting simulations in the Unity [32] is proposed in [60]. Games can build interactions using physics engines and simulators such as the PhysX (v9.23.1019) [61]. PhysX supports rigid and body dynamics and volumetric fluid simulation.

2.1.2. Serious Games

Several serious games have contributed to this work subject. Serious games consider learning objectives and learning outcomes as fundamental design considerations and thus are considered more appropriate for game-based learning [62]. The Woodwork Simulator [63] provides reasonable approximations of the effect of virtual saws, drills, glue, chisels, and sandpaper on virtual wood. In [64], simplified tool interaction is used to shapes metallic pieces. In [65], calculus is made more interesting, intuitive, and educational. In [66], glasswork actions are simulated in MR. Pottery simulations involve the manipulation of clay on a rotating wheel. In [67], a haptic simulation of pottery-making provides users with tactile feedback, enhancing the realism of the experience and enabling the replication of traditional techniques. Metalworking processes such as forging, casting, and machining involve significant physical transformations. In [68], deformable models that simulate the plastic deformation of materials, which are essential for creating realistic simulations of metalworking operations were developed.

Remote, but still relevant, interactive simulations for mechanical assembly enable the virtual assembly of mechanical systems, providing insights into the assembly process and the interactions between components. In [69], a system for simulating the assembly of mechanical parts was developed, enabling users to explore different assembly sequences and detect potential issues.

2.2. Physics-Based Simulation

Physics-based simulations focus on the physical behavior of mechanical systems including structures, materials, and dynamics. The FEM is foundational to many mechanical simulations and was popularized by Clough and others in the 1950s [70,71]. The FEM was applied primarily to civil engineering problems [72], and the aerospace and automobile industry played a crucial role in driving their early adoption [73]. FEM simulations [74,75] were originally used for industrial applications like automotive design and structural mechanics [76] including crash test simulations [77,78]. Finite Element Analysis (FEA) [79,80] utilizes the FEM for physical systems simulation. Geometrically, physical bodies are represented as volumetric meshes by finite elements. The behavior of the system is described by a set of mathematical equations based on the physical laws governing the problem. In this work, the FEM is employed to model the fine details of material deformation and tool interactions, especially in artisanal and craft-based activities. For example, recent research illustrates how the FEM can accurately simulate cutting processes by modeling mechanical stresses, tool wear, and material deformation [81–83]. More recently, the FEM has been used in simulating complex tasks such as interlocking and forming, where multiple materials or objects were studied [84].

The commercialization of FEM software made these tools more widely accessible to engineers across various industries. Notable commercial FEM software include ANSYS [85], NASTRAN [86], and Abaqus [87]. Parallel software suites like FLUENT and CFX are proving to be instrumental in advancing the field of Computational Fluid Dynamics (CFD) [88,89].

Traditionally, generic and interactive simulations are based on “physics engines” [90]. Physics engines simulate rigid objects, their potential collisions, and their behavior thereafter [91]. Nevertheless, if real-time performance is required, the structural complexity of the involved models has to be low (i.e., their 3D meshes should comprise few polygons.

Scientific simulation has not been widely adopted in the domain of crafts. Some limited and remotely relevant examples include the formation of nots, mechanical models for fibers, and metalworking processing [92–94].

2.2.1. The Potential of FEM Simulations in Human Activity Simulation

In this paper, more general simulations of human behaviors were utilized to inform us about the making process. In crafts and manual work, human tasks are characterized by operating tools and processing materials under force, pressure, or movement. The FEM becomes a simulation of these interactions through the stress, strain, and deformation of objects. The simulation can do a lot more than just setting up the scene. It can compute several important parameters such as pressure, angle, speed of tools, etc. This allows the FEM to produce highly detailed and physically based simulations of human–tool interactions, which are otherwise challenging to model utilizing traditional animation or approximation techniques. Directions have been examined in areas such as craft [95–97], surgery [98,99], and the sports domain [100,101]. In this work, we will argue that as the FEM is highly capable of synthesizing a vast sequence of processes, it can be leveraged in immersive training situations to provide a realistic practice environment in which users will train to manipulate virtual objects while acting under physical constraints. An example of this is a craftsperson learning to carve wood. Testing various levels of pressure and tilt angles while using virtual woodworking tools can help understand the properties of the material without any damage or material waste.

2.2.2. FEM Simulations for Learning

The FEM can be used in fields that require a deep understanding of physical systems, material behavior, and structural mechanics. FEM simulations enable learners to visualize and interact with complex physical phenomena, providing insights that are difficult to achieve through traditional teaching methods. By integrating FEM with AR, engaging training environments can be built that enhance learning outcomes.

FEM-based simulations have been widely adopted in engineering education to teach structural mechanics. These simulations allow students to explore the behavior of structures under various loading conditions, providing a hands-on understanding of concepts such as stress, strain, and deformation [102,103]. In fields such as magnetics and electromagnetics, AR systems that integrate FEM simulations have been developed to enhance training. These systems allow learners to visualize magnetic fields and their interactions with materials in real-time, providing a deeper understanding of complex concepts [104,105]. In medical education, FEM simulations are increasingly being used. These simulations provide a realistic environment for training in surgical procedures and diagnostic techniques [106,107]. In material science education, FEM simulations are widely used to model the behavior of materials under various conditions, such as stress, temperature, and pressure. These simulations help students understand the properties and performance of different materials [108,109]. In the aerospace and automotive industries, FEM simulations are extensively used for training engineers in structural analysis, crash testing, and fluid dynamics [85,110]. The FEM is a cornerstone of civil engineering education, where it is used to model the behavior of structures such as bridges, buildings, and dams. These simulations help students understand the principles of structural analysis, design, and mechanics. In this context, several applications have been developed that combine AR with FEM simulations to provide immersive training (e.g., [110,111]).

2.2.3. Three-Dimensional Rendering of FEM Results

FEM simulations can be transferred in 3D, using software platforms and game engines such as Blender (v3.6) [112] and Unity3D (v2021.3.24f1) [32]. These allow FEM-generated data to be converted into 3D models and 3D animations [113]. Studies have been researching the usage of FEM simulations in AR for real-time evaluation of mechanical tasks for training purposes [114]. These simulations enable users to experience factors that are critical in training processes [115,116] such as material deformations. At the same time, lighting, textures, and high-res materials can enhance realism, making it easier for trainees to learn by replicating real-world conditions. This can be further supported by advances in photorealistic rendering [117,118] to better simulate the appearance of materials under various lighting conditions.

2.3. Immersive Training Applications

2.3.1. Training and Human–Tool Interaction

Human–tool interaction simulations in virtual environments leverage a variety of techniques, including haptic feedback, physics-based modeling, motion tracking, and immersive technologies like VR and AR. Examples include modeling tool–tissue interactions for surgical simulations [119] and the integration of haptic systems in minimally invasive surgical training [120,121]. These works demonstrated how tactile interaction and realistic haptic feedback can improve precision and user engagement. Other methods introduced the simulation of surgical cuts in real-time, addressing computational challenges while ensuring visual and interactive fidelity [122]. Expanding beyond medical contexts, haptic feedback has also been explored in generic tool manipulation applications [20,22]. In the same context, the use of motion tracking to simulate tool interactions in virtual environments, focusing on realistic avatar animations has also been considered [24]. This has found application in interactive assembly simulations, showcasing its potential to refine manual dexterity and decision-making [123,124]. Another relevant example is the VR-based welding simulator that illustrates how immersive environments can be used to train in crafting activities [125].

2.3.2. Data-Driven Animation for Virtual Environments

Data-driven animation creation is an approach for producing realistic and dynamic visual content, leveraging data-driven and physics-based techniques. Simulated physics forms the backbone of interactive character animation, enabling the synthesis of lifelike movements that adapt dynamically to varying environmental conditions [126]. This approach has been extended to specific anatomical models, such as 3D neck modeling [127]. Regarding animation in virtual environments, precomputing data for specific scenarios, such as tree animations, demonstrates the efficiency of data-driven techniques in generating realistic, complex natural phenomena [128]. High-resolution animations of dynamic effects like fire have also benefited from data-driven approaches, enabling visually striking results through the integration of simulation and synthesis [129]. For fluid simulation, the data-driven projection method offers improved accuracy and computational efficiency, which enhances the fidelity of fluid-related animations [130].

2.3.3. Effectiveness of Virtual Environments and User Interfaces as a Training Tool

Virtual environments and interfaces have proven to be effective tools for training, offering immersive and engaging learning experiences across various disciplines. Systematic reviews have highlighted the ability of VR to enhance cognitive and procedural learning outcomes, particularly in complex subjects such as science, engineering, and medicine [131,132]. Immersion in VR can support mastering skills without real-world risks [133,134]. Research also demonstrates that VR-based training improves retention rates, learner engagement, and motivation, which are critical for long-term skill acquisition [39]. Additionally, the adaptability of virtual interfaces allows for personalized and self-paced training [135,136].

2.3.4. Challenges and Opportunities

The primary challenge is probably ensuring that the virtual environment accurately replicates real-world conditions, particularly in terms of the physical interactions between tools and materials such as by superimposing objects in space [137]. In [138], a Head Mounted Display (HMD) is used to present traditional craft objects with high presence and absorption. In [139], AR is used to augments a physical object with audiovisual assets. In [140], visitors can perform woodworking tasks.

2.4. Main Contributions of This Research Work

This research presents a unique approach to the simulation of craft actions in immersive education environments. The method involves the development of reusable motion animators that are incorporated into VR systems to simulate complex crafting actions. The combination of FEM simulations with 3D rendering technologies and haptic devices creates an educational solution that provides sensible feedback to trainees. The main contribution of this work is the provision of a methodology for combining FEM simulations with VR education. At the same time, the creation of motion animators allows the reuse of FEM simulation results across different education situations. The integration of photorealistic rendering techniques complements the realism of the training environment at the same time as using haptic controllers can help realistic tactile interactions.

Key advancement is the use of the FEM for simulating human activity which is well-established in fields such as medical training, material analysis, and mechanical engineering. However, its application to cultural heritage, specifically in the context of preserving and training for traditional handcraft processes, presents distinct challenges and particularities. Unlike other domains, the focus here is on capturing the interaction between tools, materials, and human activity in an accurate way to replicate the tactile and procedural interactions of traditional crafts. This necessitates a detailed understanding of craft-specific materials, techniques, and workflows which is often the standardization seen in other applications of the FEM. At the same time, accurate reproduction is of extreme importance for the efficiency of training which is not always the case for industrial simulations such as assembly line operation, machine operation, tool manipulations, etc.

3. Proposed Method

The proposed methodology (see Figure 1) has a simulation and a training phase. The simulation phase regards the generating of animation for craft reenactment based on the studied craft instances and their simulation while the training phase regards the authoring of training lessons, their assignment, and execution in the context of immersive training scenarios.

The simulation phase begins with analysis to identify actions that influence the state of materials, such as human activity and machine operations, as well as those that do not, such as the position and orientation of tools or the machine states. This process provides the simulation characteristics that assist in identifying whether a more complex FEM-based simulation is required or whether the action can be simulated using simple operations executed in a game engine.

Regarding FEM-based simulation time, space, tools, and materials, it is initially defined in a FEM modeling tool. Object movements, material properties, and force interactions are modeled to accommodate both rigid and deformable material behaviors. The outputs of the execution of these simulations are preprocessed to generate results that explore the parameter space. These results are organized into lookup tables with key values in the domain of the parameter space. In the animation phase, the implemented lookup tables are used to create animations per lookup table key value. These animations are all combined into Action Animators which are collections of animations per action. Multiple Action Animators are combined into Animation Packages. Each Animation Package represents a complex craft process of a craft instance according to the complexity of the craft under study.

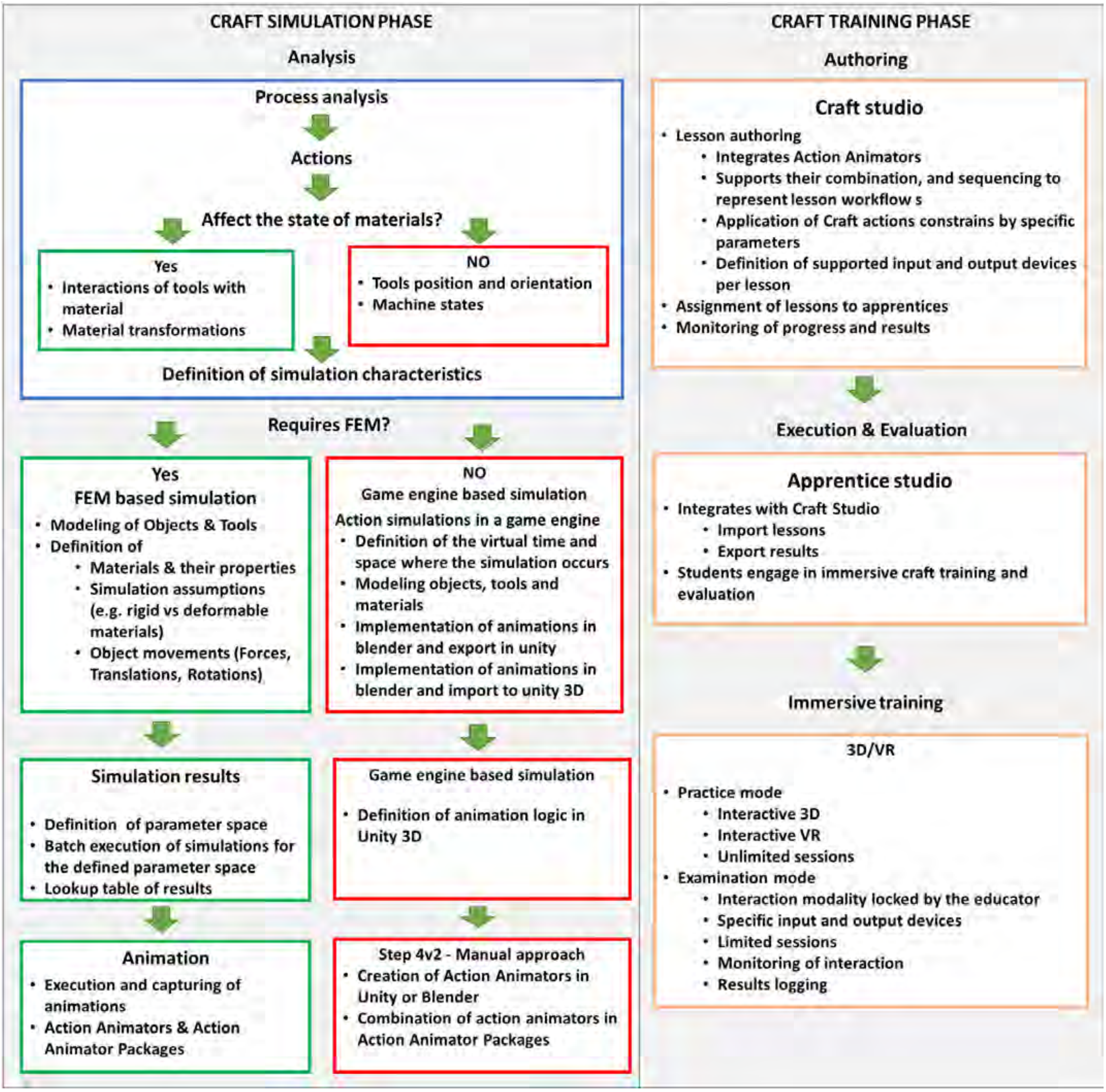


Figure 1. Overview of the proposed methodology.

In the case that the intention is to proceed with game-engine-based simulation tools like Unity 3D or Blender are used to create virtual representations of actions. This approach focuses on modeling and animating dynamic action sequences directly in the game engine. The authored animation logic is manually adjusted to resemble what is happening in reality (e.g., a chisel is cutting a piece of wood following the prescribed motion).

During the Craft Training Phase, the results of the simulations are used to synthesize immersive learning experiences. The process starts with authoring conducted with the support of the Craft Studio which is an authoring tool that integrates animations to construct and customize lesson workflows. This tool supports lesson creation, assignment, and monitoring of trainee progress and outcomes. Execution and evaluation are facilitated through the Apprentice Studio, which enables immersive engagement with crafted lessons. This environment supports the import and export of lessons, the application of parameter constraints, and the integration of devices to enhance realism in training scenarios. Finally, immersive training offers two modes of operation. Practice mode provides unlimited interactive sessions using 3D or VR technologies. The examination mode delivers structured assessments with predefined parameters, enabling a focused evaluation of trainee performance.

3.1. Execution of the Craft Simulation Phase

3.1.1. Analysis

The analysis is supported through the application of ethnographic strategies with on-site fieldwork, where researchers get to know the location where the craft is practiced. This involves spending time in workshops but also communicating with craft masters. At the same time, observing them as they carry out their work is of importance. Interviews are also employed to capture experiential knowledge, focusing on how craft masters describe their methods, the purpose of each tool, and the characteristics of the materials they work with. Another important aspect is observation, where the researcher may engage in the craft themselves, learning from the artisans through hands-on experience.

The result of this review is the definition of a process map that details the sequence of actions involved where each action is divided into subactions that need to be identified and categorized. Actions include subtraction (e.g., carving or cutting), formation (e.g., bending or molding), interlocking (e.g., joining or fastening), and addition (e.g., gluing or applying coatings). The review also identifies the variability in how these actions since different craft masters might use different techniques or tools to achieve similar outcomes.

Equally important is the identification and documentation of the equipment used in the craft, categorizing the tools according to their function, and documenting their specific characteristics, such as size, shape, and material composition. The material properties of the resources used in the craft, such as the type of wood, metal, or clay, must also be documented. Understanding the material's behavior—how it responds to different forces, temperatures, and environmental conditions—is essential for accurately simulating the craft process in later stages of the methodology.

3.1.2. FEM-Based Simulation

Actions performed by humans in the context of crafts involve interactions between tools and materials, which can be challenging to replicate virtually without precise physical modeling of the tools, the materials, and the action itself. In this work, we build virtual representations of such action in the form of a FEM model in Simulia Abaqus, focusing on the simulation of various crafting actions (e.g., subtractive, formative, interlocking, and additive processes). Simpler actions are directly modeled in Blender and imported to Unity3D or directly authored using the Unity3D animation pipeline [32].

FEM simulations are created by authoring actions in Simulia Abaqus. The simulation operates in virtual time and space, where events are discretized into time frames. Objects, tools, and materials are modeled in 3D. The properties of the materials of the objects contributing to a simulation are important for realistic simulations. Properties like density, Young's modulus [141], ductility, and elastic modulus are considered. Young's modulus is a measure of stiffness and is given by

$$E = \frac{\sigma}{\varepsilon}$$

where σ is defined as the stress and ε is defined as the strain.

Tools are categorized by their function, such as cutting, gripping, or driving, with mechanical principles like leverage and torque simulated. Workpieces evolve through various craft actions, and their final form is represented based on the type of action (e.g., subtractive or additive). Forces are applied to the objects by employing linear or rotational (torque) models supported by Abaqus. These are calculated for each finite element involved in the crafting action. Movements of objects are modeled in the three-dimensional space as translations and rotations. Time-dependent actions can be included as part of the simulation process.

The execution in Abaqus of these simulations produces a results database that contains the physical properties of the tools and materials and their changes over time. Furthermore, it contains the rendering of the simulation in 3D. To make 3D simulation data compatible with game engines a transformation should be applied to create animation sequences. To this end, a Python (v3.12) script is used to extract and export the simulation results as sequences of frames. Each frame corresponds to a specific configuration of parameters, such as tool angle or applied force. To simplify the usage of these sequences naming conventions per frame, tools and parameters are used, and lookup tables are created to allow the indexing of results. The indexed data are then processed to create animation clips.

The action is simulated for a broad spectrum of rotational angles to cover a wide range of possible user interactions. Each set of angles in the parameter space is used to perform individual simulations. The same approach is applied to other parameters like tool speed, force applied, or environmental conditions (e.g., temperature). Next, these animation sequences are integrated into lookup tables encapsulated into a reusable component designed for game engine integration, called an Action Animator. An Action Animator contains all the simulation data and the logic to execute craft actions in the form of game engine animations. These include (a) predefined animation frames representing various states based on different parameter configurations (e.g., tool angle or applied force), (b) simplified mesh representations optimized for rendering performance, and (c) transition logic handling the interpolation between different frames and parameter values. Multiple Action Animators can be combined into a package. New Action Animators can be added to the package, ensuring scalability and flexibility.

3.1.3. Game Engine-Based Simulation

In the case where the studied actions do not involve material deformation such as simple mechanical operations, a game engine can be used to produce real-time interactions and kinematic animations with sufficient accuracy. Relevant craft actions are identified by studying the ethnographic review. Once the simulation has been defined, it is executed and the simulation results are acquired. The results are by design compatible with the game engine and available in real-time thus requiring no further processing. In Unity3D [32], the craft tools and objects are represented as 3D models, and their movements are controlled using rigid-body physics. Action Animators for these kinematic operations are executed by the game engine by controlling the motion parameters of the engaged objects. To enhance realism, collision detection, and basic interaction models are incorporated into the game engine. Although the FEM is not needed, the collision between objects (e.g., the glass-blowing rod and a support stand) is still simulated to ensure accurate physical behavior.

3.2. Execution of the Craft Training Phase

In the Craft Training Phase, the results of the simulations are used to synthesize immersive learning experiences following a three-step process.

3.2.1. Authoring

Authoring of immersive experiences is supported by a software called Craft Studio. Its primary functionality is to support designing, configuring, and specifying lessons that simulate real-world crafting tasks within a virtual space. Craft actions in the lesson can be constrained by specific parameters, which serve as restrictions to ensure the accurate performance of actions. Parameters such as tool angle, force, speed, and environmental conditions (e.g., temperature) can be adjusted. Regarding the parameters of execution, Craft Studio provides input and output devices that can be used during the training session. Once the lesson is fully designed a lesson specification is generated. This specification is a set of instructions and configurations that defines the crafting task and serves as a blueprint for executing the training session.

The Craft Studio supports visual diagrams for lesson creation to allow craft masters to map the training process. Lessons can be previewed in real-time, ensuring that all components are correctly linked and functioning as intended. Each educator accesses the Craft Studio using his credentials. This is to organize lessons per educator and allow monitoring of students, assignments, and results. A lesson can be considered as a flow diagram that contains Virtual processes and Virtual actions and their logic for their connectivity. An execution of a lesson is the execution of the flow diagram. Each node of the diagram is assigned some criteria that regard the input parameters and the success criteria. Moving from one node to another requires that these criteria are met. Nodes can be executed in parallel or sequentially or even based on branching points where several parameters are checked. Lessons are composed using Virtual processes and Virtual actions. When imported in a lesson an Action animator will be rendered for each Virtual action using the assigned parameters. A Virtual process is a combination of Virtual actions linked under specific conditions. Virtual actions are imported, while Virtual processes can be both imported and authored in the Craft Studio.

3.2.2. Execution and Evaluation

The execution and evaluation of training courses are supported by a software called Apprentice Studio. Its primary purpose is to provide an interactive, structured environment for craft students to develop, practice, and demonstrate their skills. It provides access to the created lessons designed in Craft Studio and incorporates study and examination modes. In Study Mode, real-time feedback helps students refine their techniques, while the post-examination reports provide detailed insights into areas for improvement. The Examination Mode provides a standardized and objective mechanism for assessing students.

Each lesson corresponds to a specific task or set of tasks represented by a collection of Action Animators and associated lesson parameters. In Study Mode, students interact with the lesson in a guided, hands-on environment. This mode allows students to practice specific craft actions with real-time feedback. During this study, the system tracks student inputs (e.g., tool angles and force applied) and compares them to the predefined constraints set in the lesson specification. Immediate visual and/or auditory feedback is provided to help students adjust and refine their actions, ensuring that they understand the precise execution requirements of the craft.

In Examination Mode, the student transits from practice to formal evaluation. Here, the lesson parameters are used to assess the student's ability to perform the craft task accurately and within the predefined restrictions. The examination mode differs from the study mode in that feedback is withheld during execution, requiring the student to rely on their knowledge and skills developed in practice. Metrics are used to generate a quantitative score, representing the student's proficiency in the craft action being evaluated. After completing an examination, the system provides the student with a detailed report of their performance. The Apprentice Studio's design has been conducted in Figma UI design [142] service and then was imported into Unity3D [143] (see Figure 2). When entering the Apprentice Studio, the splash screen contains the collection of courses assigned to the specific student. Courses are categorized by their completion status.

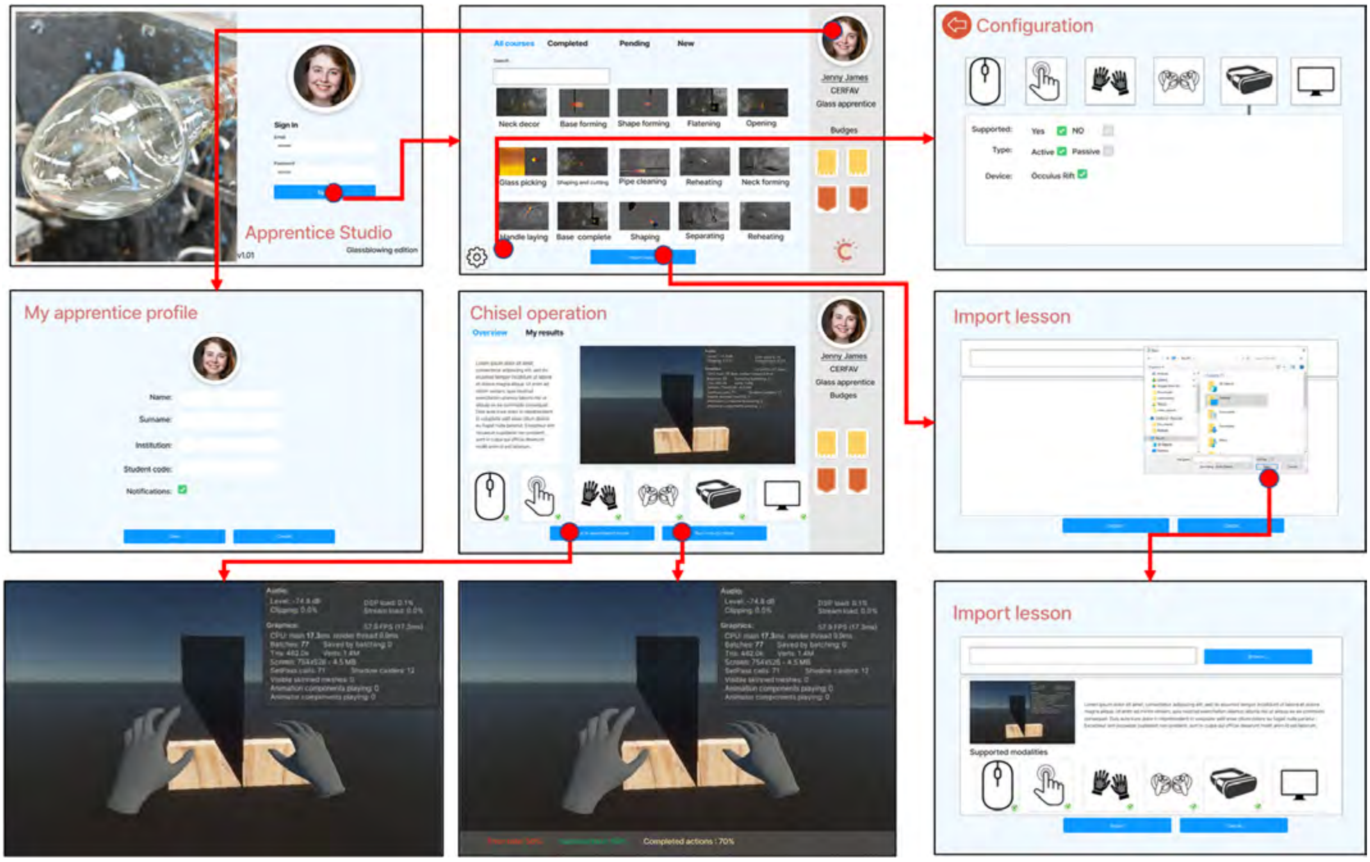


Figure 2. Workflows of Apprentice Studio.

3.2.3. Immersive Training

The final step of the methodology involves adding interactivity through more complicated inputs and outputs in the context of immersive training (Step 3). Regarding inputs, the standard controllers of the Meta Quest 2 are used combined with the possibility of adding custom haptic controllers for specific operations. Regarding outputs complementary to the 3D rendering in a monitor, stereoscopic rendering through the HMD is supported to enhance the immersivity of the training scenarios.

Immersive training allows learners to participate in virtual simulations that mimic real-world craft activities. In these activities, three types of input devices are supported. Keyboard and mice, support the performing of tasks but offer less immersion compared to specialized controllers, but are accessible and familiar, making them suitable for introduction or desktop-based drilling.

Custom tactile controllers are designed to provide physical resistance and force feedback, mimicking the feeling of working with real materials (such as wood resistance when using fleas). These devices are constructed for specific technological actions and provide very realistic feedback aligned with the power experienced in real work. The haptic controller not only tracks accurate movements but also reproduces tactile and force feedback associated with the actual work, providing the highest level of immersion.

Regarding Output devices are essential in providing visual and sensory feedback and improving overall presence and realism in virtual environments. A standard computer monitor provides a basic visual depiction of a virtual space. This is sufficient for keyboard and mouse operation but lacks the depth and field provided by more sophisticated equipment such as VR headsets that completely immerse the user in a 3D environment and perceive the spatial relationship between tools, materials, and hands in real-time. When combined with VR controllers or custom haptic devices, the combination of visual and physical feedback creates a real simulation of the creation of the action.

4. Case Studies

This section presents the implementation of the method with examples from studies on wood carving, and glassblowing for demonstration. In wood carving, we employ FEM-based simulation while in glassblowing we employ game-engine-based simulation.

4.1. Craft Simulation Phase Implementation and Case Studies

4.1.1. Case Study—Analysis

For the Analysis step, an example from the segmentation of an ethnographic recording is presented. This example consists of part of the recording of the craft process and the action under investigation regards creating a woodcarving design using a chisel. The segment concerns an Egocentric camera recording of the second practitioner contributing to the ethnographic analysis and has a length of 11′29. It presents the action initiation and the action iteration to create a horizontal wood carving. The process starts at the work table, where there is a piece of wood clamped into the working bench. The action under investigation regards the creation of a wood trim following the pattern of the object created. The action is performed with a solid tool (a sharp scalpel). The action is segmented to isolate the carving action (see Figure 3). Following the above-mentioned segmentation and documentation process, the ethnographic analysis provides a good understanding and video representation of the craft under investigation.


(**a**) (**b**)

Figure 3. (**a**) Start pose; (**b**) end pose.

4.1.2. FEM-Based Simulation

The next step involves the transformation of the above-described analysis into a FEM simulation in Simulia Abaqus. This involves defining the geometrical model, material properties, boundary conditions, and the mechanical interaction between objects. The authoring starts by defining the objects involved as 3D geometries. The wood block is typically represented as a rectangular solid and the chisel as a sharp, wedge-shaped tool. The sharpness of the chisel is a critical aspect of the geometry, as it influences the stress concentration at the contact point. Chisel's Geometry is defined as a rigid body with a defined angle of attack. The chisel's cutting edge is modeled with sufficient detail to capture the effects of material cutting. Wood Block's Geometry is modeled as a deformable solid, where the dimensions of the block are defined to allow enough space for the chisel to penetrate and interact with the wood. Wood is treated as an anisotropic material and its mechanical properties vary to simulate the natural grain structure of wood. The material model used for wood includes (a) Density which determines the mass and inertia of the wood, (b) Stiffness of the wood and how it reacts to tensile and compressive forces, (c) Plasticity and Damage Models for simulating the cutting process since the wood undergoes plastic deformation, and (d) Friction between the chisel and wood. The chisel is treated as a rigid body in this context, meaning it does not deform under the applied forces. Since wood is anisotropic, its stress–strain behavior is represented using a compliance matrix (Hooke's Law for Anisotropic Materials [144]):

$$\sigma = C\varepsilon$$

σ is the stress vector, ε is the strain vector, and C is the anisotropic stiffness matrix, which depends on the elastic properties in different grain directions. A fine mesh is applied to the surface where the chisel will contact, ensuring accurate simulation of local deformations. The angle of the chisel's insertion and rotation serves as the variable of interest. The force applied by the chisel (F_c) is decomposed into normal and tangential components due to the cutting angle (θ):

$$F_n = F_c cos(\theta),\ F_t = F_c sin(\theta)$$

where F_n is the normal force responsible for indentation, and F_t is the tangential force responsible for material removal. The Contact Pressure Between the Chisel and Wood is given by

$$p = \frac{F_n}{A}$$

where A is the contact area, which depends on the penetration depth and chisel edge geometry. The material failure is modeled using a yield criterion, such as the Tsai–Wu failure criterion [145] for anisotropic materials:

$$F_1\sigma_1 + F_2\sigma_2 + F_{11}{\sigma_1}^2 + F_{22}{\sigma_2}^2 + F_{12}\sigma_1\sigma_2 = 1$$

where σ_1 and σ_2 are principal stresses in the wood grain directions, and F_1, F_2, F_{11}, F_{22}, F_{12} are material-dependent coefficients. The frictional force (F_f) Between Chisel and Wood follows Coulomb's friction law [146]:

$$F_f = \mu F_n$$

where μ is the coefficient of friction, determining the resistance during cutting. Energy Dissipation Due to Cutting is expressed as

$$W = \int F_c d_x$$

where dx is the incremental displacement of the chisel. Deformation and Strain Energy (U) stored in the deformable wood block is given by

$$U = \frac{1}{2}\int_v \sigma\ :\varepsilon\, dV$$

where V is the volume of the wood block.

Boundary conditions and contact interactions are defined based on the above considerations. The wood block is constrained to prevent movement, simulating the effect of clamping. The chisel is given a prescribed motion, typically a downward or rotational force, to simulate the cutting action. The chisel's motion is modeled through the application of a displacement-controlled load or a force-controlled load, depending on the specific scenario being simulated. In a displacement-controlled simulation, the chisel is moved at a predefined speed into the wood, while in a force-controlled simulation, a specified force allows the chisel to move based on the resistance of the wood.

The simulation is executed in a series of steps each of which is computed using a dynamic solver in Abaqus. Once the simulation is complete, the results are processed to analyze the behavior of the wood under the action of the chisel. The key outputs include (a) Stress and Strain Distribution visualizing the areas of maximum stress in the wood, (b) Deformation visualizing the degree to which the wood deforms as the chisel penetrates, indicating how efficiently the tool cuts into the material, and (c) Material Damage and Failure representing areas where the wood has exceeded its failure criteria are identified, showing the material removal process (for results, see Figure 4). A detailed description of the setup of the simulation is presented in Table 1.

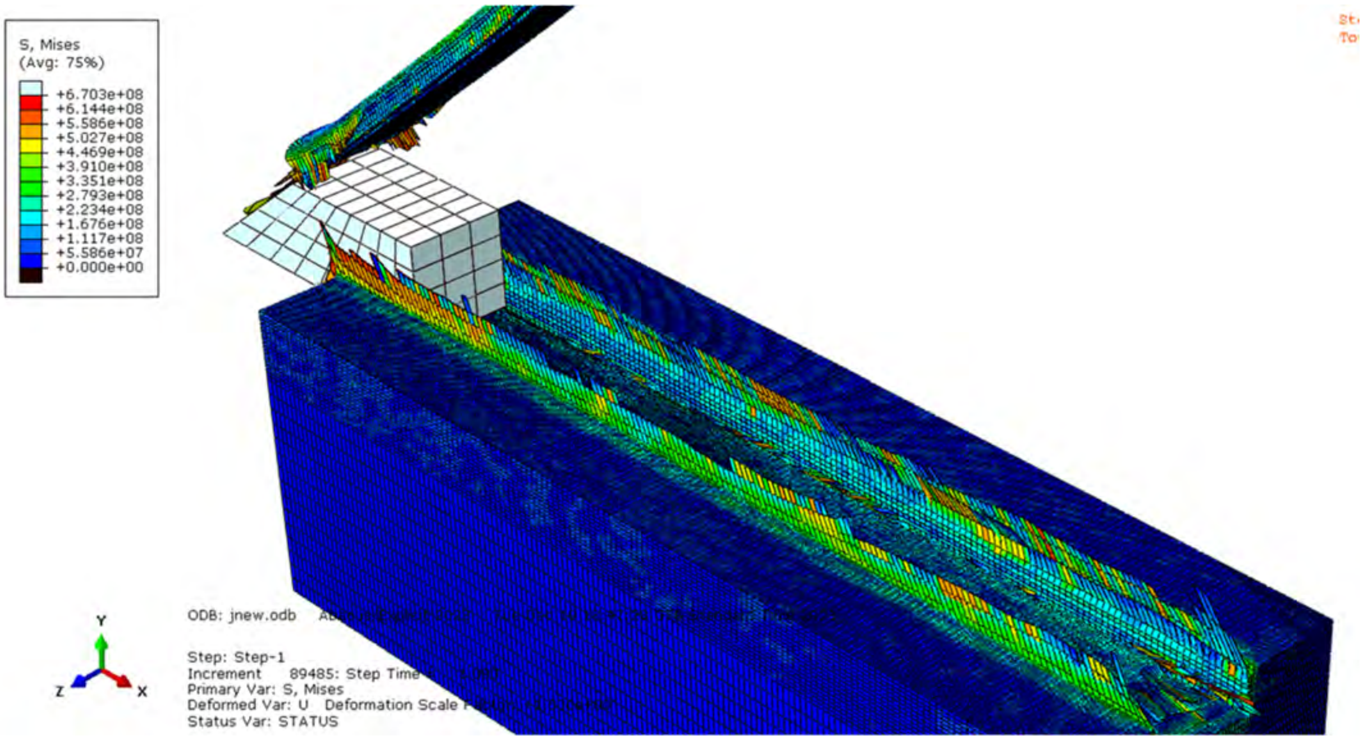


Figure 4. Chisel action simulation.

Table 1. Simulation setup and execution parameters.

Chisel (Rigid)	Type: 3D—Rigid part Total number of elements: 136 linear quadrilateral elements of type R3D4 Approximate global size = 0.0003 Area centroid of shell faces: 0.0306, -3.37×10^{-4}, 5.00×10^{-4}
Wood Block (Timber)	Type: 3D solid—Deformable part, 742,500 linear hexahedral elements of type C3D8R Approximate global size = 0.0007 Volume: 9.00×10^{-8} m^3 Volume centroid: 0.0643, −0.0359, 0.00150 Mass: 2.43×10^{-4} Center of mass: 0.0643, −0.0359, 0.00150 Density of timber = 650 kg/m^3

Table 1. *Cont.*

Simulation properties	Step: In the simulator, we use a dynamic explicit time step with a duration of 1 s. Interaction: In the simulator, we use a surface-to-surface interaction to model the contact between the chisel and the block. The coefficient of friction (μ) between the rigid part and the wooden block is approximately 0.4. Duration of the simulation: 6 h, 52 min, and 27 s.

To address the need for variability in the presentation of simulated crafting actions, we precompute a set of FEM simulations using a range of predefined parameters. To do so we have to define a collection of input files for the Simulia Abaqus, each one containing the specific parameters that will be used for the execution of the simulation. This will allow us to batch-process these files to generate a collection of result databases. Each result database (odb file) contains the results of the FEM simulation for the specific parameters. The exporting process is automated through a Python script that extracts the data related to displacements, forces, and material states at each node or element in the finite element mesh.

Then, to achieve photorealism the frame sequences are imported into Blender for animation creation. Initially, the exported geometry and frame sequences are loaded into Blender which allows control of the animation pipeline. In Blender, photorealistic textures, lighting, and materials for the animated scene can be edited. Importing is supported by a Blender plugin called Stop-motion-OBJ [147]. Imported animations contain only the meshes for the objects (see Figure 5a) and thus Blender can be employed to define other parameters of the mesh object that affect their appearance. Using Blender’s timeline, the geometry at each frame step is aligned according to the simulation results, creating a continuous animation sequence. Blender’s animation tools are used to refine the motion, ensuring that the results from the FEM simulation appear smooth and realistic. High-resolution textures are applied to the 3D models to simulate the surface details (see Figure 5b). Blender’s UV mapping tools are used to map 2D texture images accurately. The Blender animations are in turn exported to Unity [32] using a .fbx or .glTF format that preserves geometry, animation sequences, and material properties. An Animator Controller is used to manage and organize the animations structured into animation libraries. A Prefab that packs all the animations together is created and a script handles the logic of selecting the most appropriate animation based on input parameters. The script takes input parameters such as chisel angle, cutting speed, or force application and maps parameters to the corresponding animation in the lookup table. In Unity, a real-time lighting system, including global illumination and real-time shadows, is configured to provide dynamic lighting.

4.1.3. Game Engine-Based Simulation

In the case of game-engine-based simulation, these occur in the form of animation sequences that alter the appearance of game objects. Their variations are calculated by the game engine and relate to the user input. In this work, main kinetic animations are employed while this does not exclude the possibility of having more complex physics-based animations (e.g., using the PhysX engine [148]). An example of such animations could involve, for example, gravity to simulate that a tool is dropped during an action due to a mistake by the apprentice. Figure 6 presents some examples of animations.

4.2. Craft Training Phase Implementation and Case Studies

4.2.1. Authoring

The authoring of training materials occurs in the implemented version of the Craft Studio. The implementation was conducted in Unity3D and it follows the same principles as the design presented earlier. An example is presented in Figure 7.

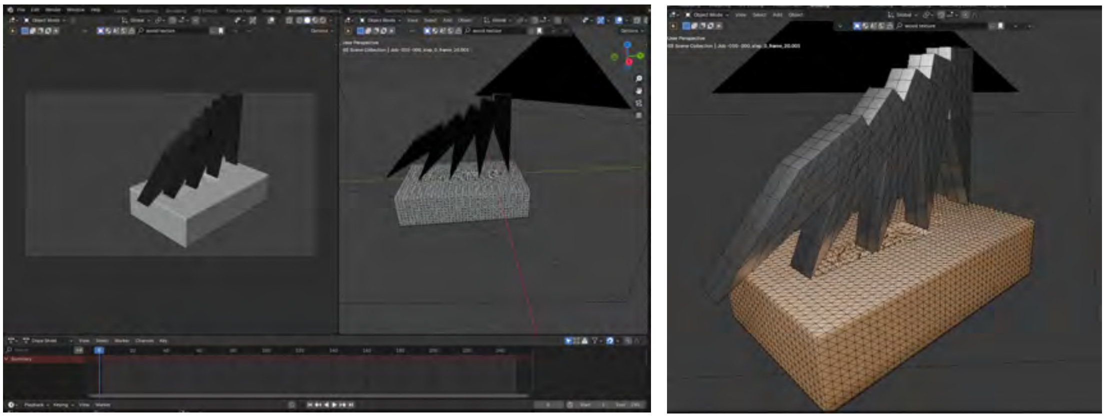

(**a**) (**b**)

Figure 5. (**a**) Animating frame sequences in Blender; (**b**) Enhancing enhancing rendering in Blender.

Figure 6. Game engine-based simulation for the glassblowing use case.

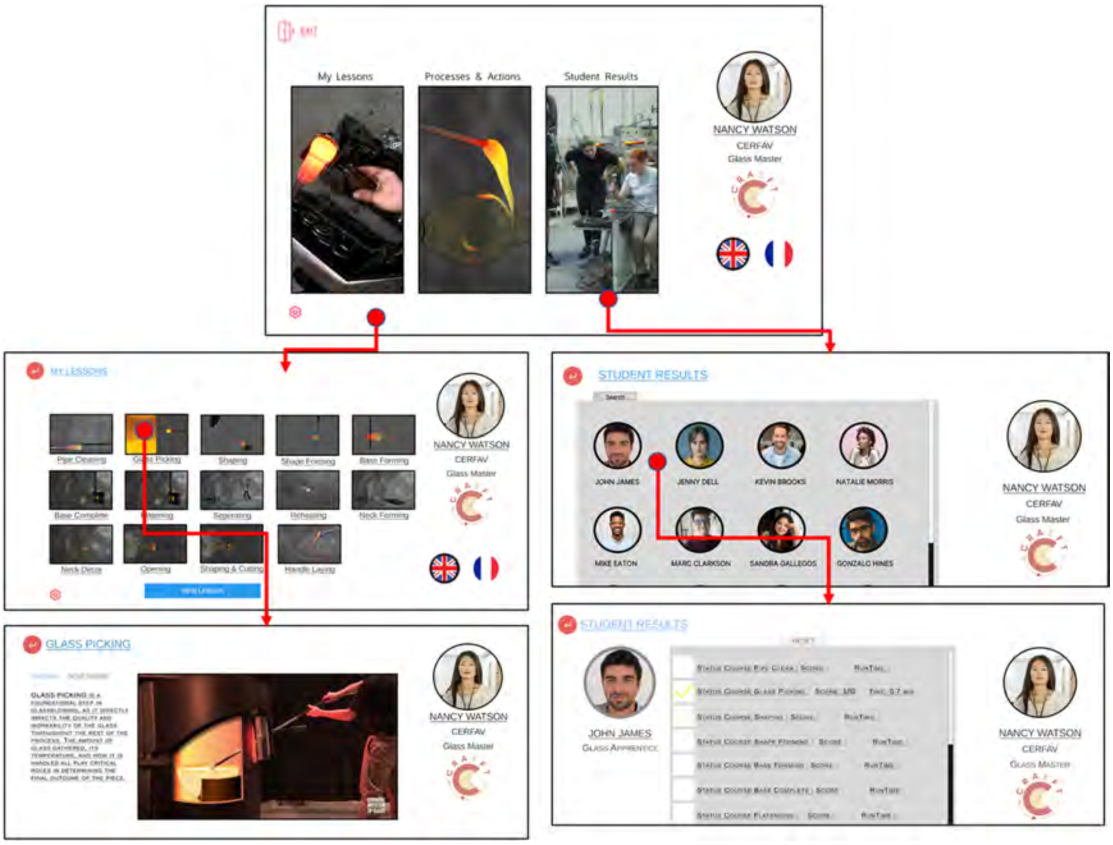
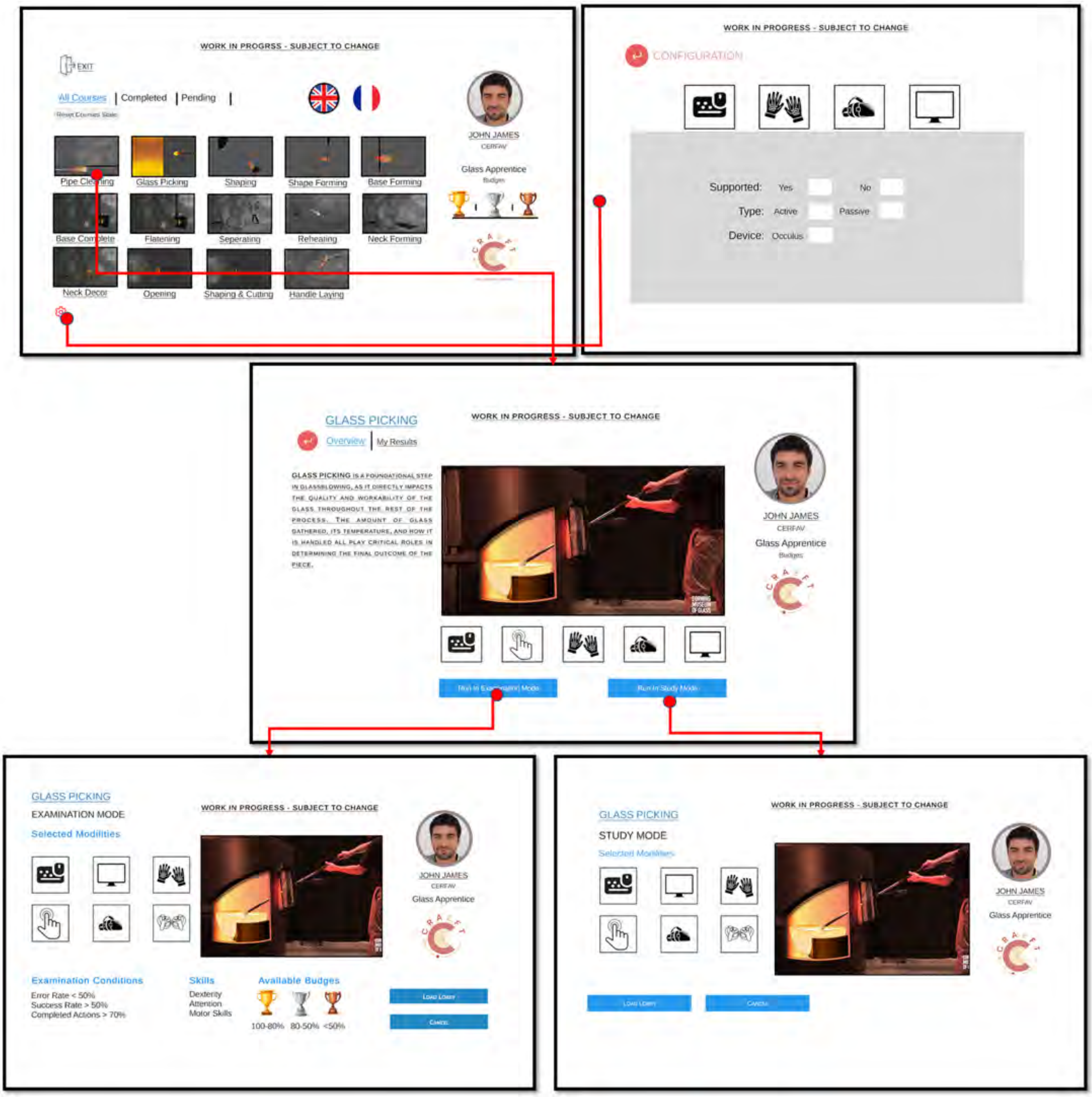


Figure 7. Craft studio workflow.

4.2.2. Execution and Validation

A lesson can be executed either in practice or in exam mode. Practice mode allows for infinite iterations for training while examination mode allows for only one iteration. The results of the examination mode can be exported and reported to the craft master. The Apprentice Studio workflow before the initiation of a training or examination session is presented in Figure 8.


GLASS PICKING IS A FOUNDATIONAL STEP IN GLASSBLOWING, AS IT DIRECTLY IMPACTS THE QUALITY AND WORKABILITY OF THE GLASS THROUGHOUT THE REST OF THE PROCESS. THE AMOUNT OF GLASS GATHERED, ITS TEMPERATURE, AND HOW IT IS HANDLED ALL PLAY CRITICAL ROLES IN DETERMINING THE FINAL OUTCOME OF THE PIECE.

Examination Conditions
Error Rate < 50%
Success Rate > 50%
Completed Actions > 70%

Skills
Dexterity
Attention
Motor Skills

Figure 8. Apprentice Studio workflow example.

4.2.3. Immersive Training

Immersive training occurs by executing a training scenario. Each execution is bound to the specific user to collect and record training data and evaluate success criteria. Two examples are presented. The first example regards solely a training course created using game engine-based animations and the second one is implemented using FEM-based simulation. In the first case, we are using the scenario of a glassblowing workshop. The task that the user should complete is to gather molten glass from the Glass Oven. To do so, the task is split into three different operations. The first operation regards locating and picking the glassblowing rod. The second action regards opening the oven. In this case, a plain interface is used without the interaction with VR controllers then a locate and keyboard click metaphor is used. In the case where VR controllers are used, a grab and move gesture is required. The same stands for the gathering process where in the case of VR this happens by aligning the glassblowing rod with the furnace and then rotating the controller. In the simplified version, key shortcuts are used for aligning the rod and for the initiation of the rotation functionality. Keyframes are presented in Figure 9.

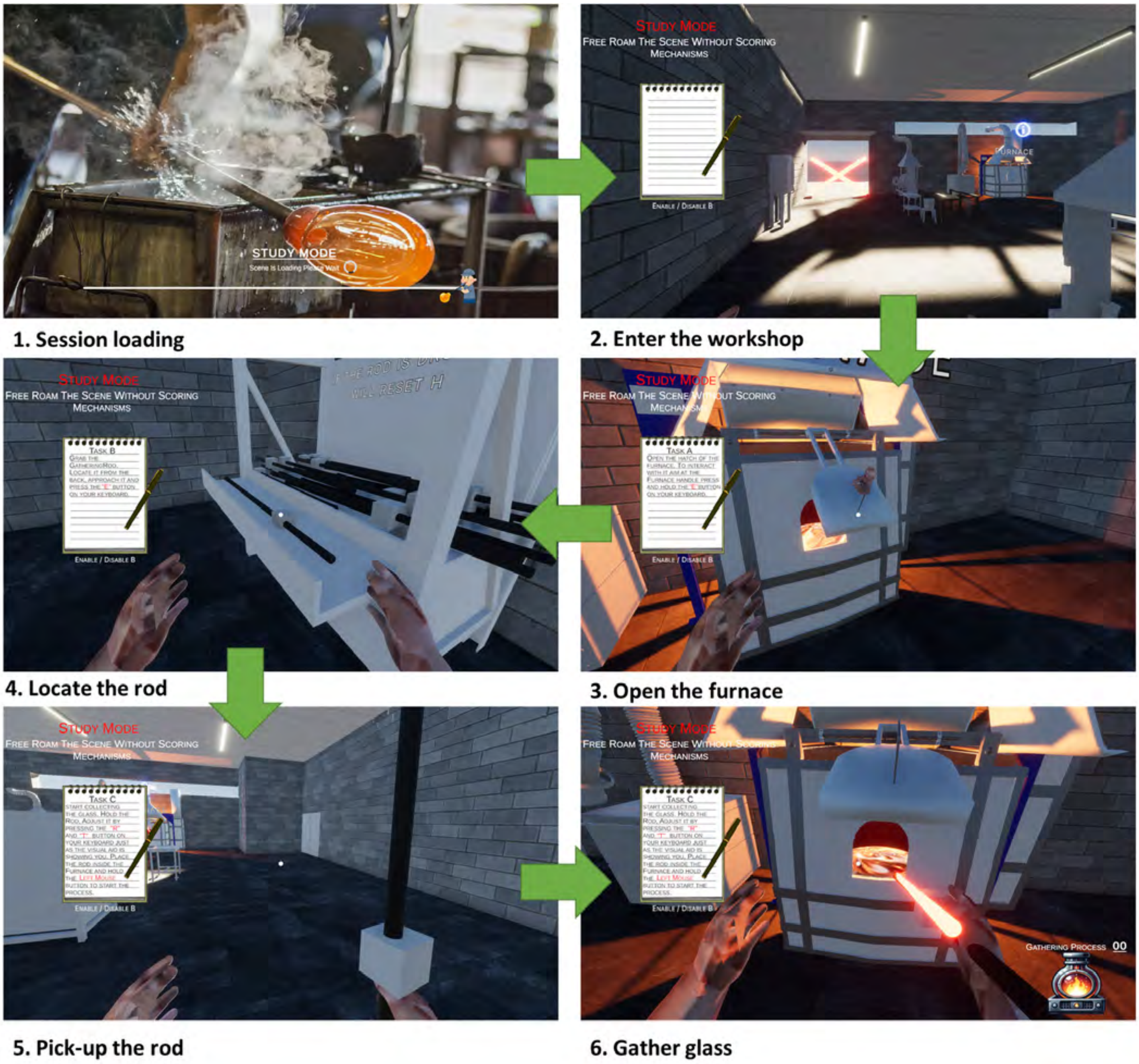


Figure 9. Glass picking training—demo.

The second example regards the chisel use case using data stemming from the FEM simulation. The user locates the woodworking bench and from there the chisel. Then, a pose for the chisel is provided by the system. The user should grab and align the chisel with the provided pose. The system provides feedback regarding the successful alignment. When the chisel is aligned the user can proceed with the action. Two variations in interaction metaphors are demonstrated, the first is VR interaction metaphor while the second is the point-and-click metaphor. The process as implemented in VR is presented in Figure 10.

Figure 10. Chisel carving interactive training—VR version.

Figure 11 shows a simplified variation in the process that uses the point-and-click metaphor. The user can select the translation and rotation of the chisel using the mouse. The usability of this metaphor is that it supports the easy and cost-effective familiarization of the user with a specific action even from home without the need to have specialized equipment. In the training mode, the system provides poses in the form of a hologram of the chisel within the screen (transparent green) and the user should manipulate the tool to match the provided poses.

4.3. Pedagogical Value

The presented methodology provides a systematic approach to support immersive learning experiences of enhanced educational value by adhering to the principles of the Cognitive Load Theory [149]. FEM based simulations and their application is a challenging subject to master. By empowering training activities with the results of the simulation methods [150–153] we are capable of training on the results without having to know the underlined principles of simulation modelling. More specifically the targeted educational courses supported by this research work address the Split-Attention Effect, by providing self-contained learning scenarios that do not overload learners. Having immersive training as another channel in the context of a learning method supports multiple sensory channels and thus enhances comprehension and retention. Furthermore, using the Expertise Reversal Effect basic eLearning content is for novice users while immersive content is for more experienced ones supporting an entirely new level of learning. Our methodology for this is supported by the combination of e-learning facilities combined with immersive training tools [154].

Figure 11. Chisel carving interactive training—desktop, point and click version.

5. Validation and Evaluation Method and Results

The proposed methodology supports a multi-layered approach towards the immersive training on craft processes empowered by FEM-based and game engine-based simulations. The evaluation and validation of such a multi-layer approach cannot be conducted on a single level of the methodology since different levels represent only a fragment of the methodology. Thus, to provide a holistic evaluation and validation of this research work several methods are employed, each best suited for each level of the proposed methodology and each stage of the development of the use cases.

5.1. Technical Validation

5.1.1. Using FEM-Based Simulation for Craft Actions

A significant part of the proposed methodology is supported through the FEM-based simulation of crafting actions. To justify the wider applicability of the approach, we extend the presentation of FEM-based simulations to a plethora of basic action simulations that are conducted to build the proposed simulation framework. In the next figure, we present an action simulation conducted in Simulia Abaqus that covers a wide range of craft actions including cutting, curving, turning, splitting, compressing, drilling, forming, and molding. This is just a subset of the proposed framework's fundamental action but succeeds in demonstrating the wide applicability of the presented methodology. All these actions are supported by the presented methodology and are fully compatible with the proposed toolchain (see Figure 12).

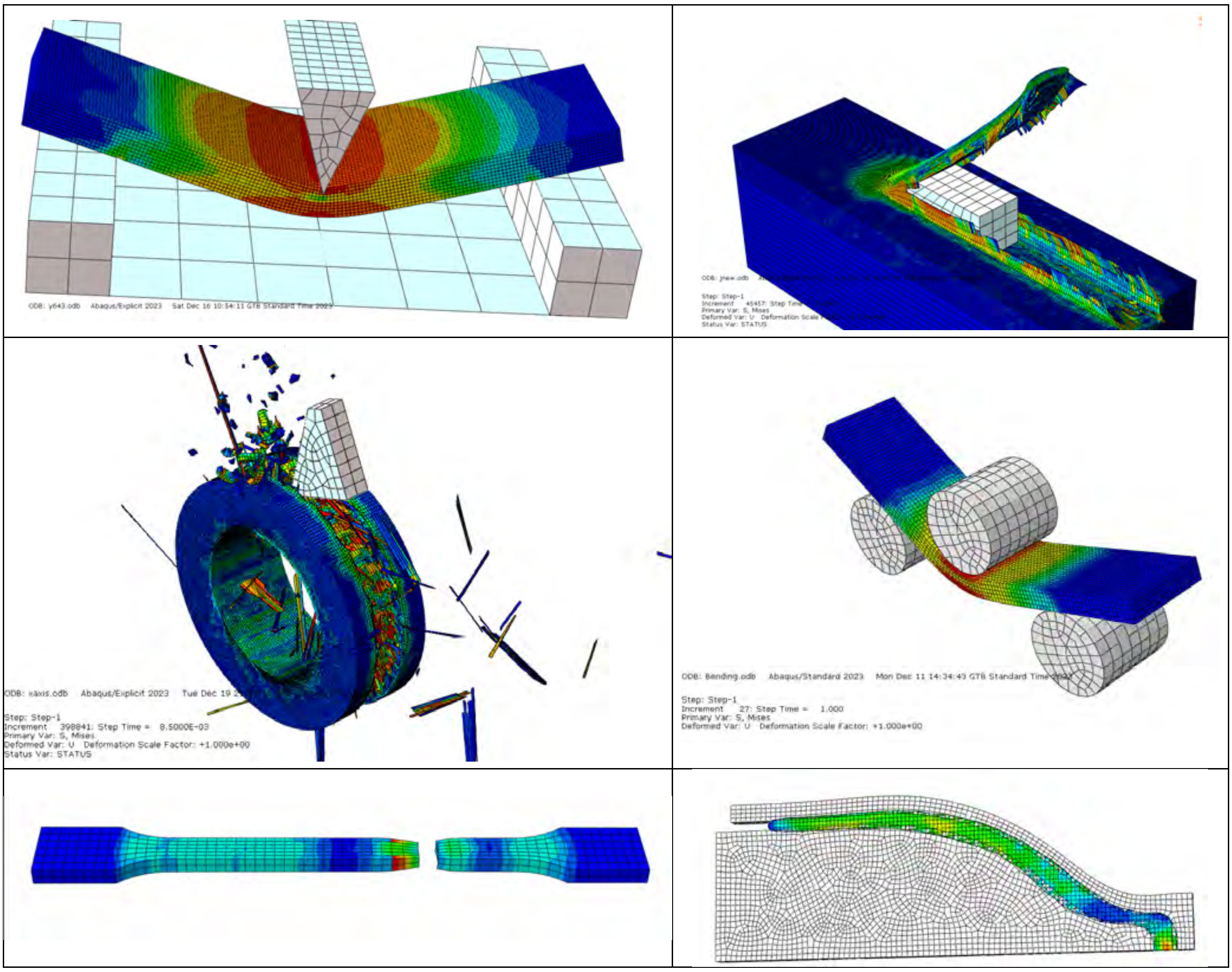


Figure 12. Simulating a wide range of craft action in Simulia.

5.1.2. Exporting Frame Sequences Using the Proposed Framework

To validate the exporting facilities offered by the proposed framework, all the presented FEM-based simulations were exported using the facilities provided by this research work. The result was more than 10 k obj files, organized into frame sequences and categorized using lookup tables. The outputs of this process were used for conducting the validation of the photorealistic rendering of crafting actions.

5.1.3. Photorealistic Rendering of Craft Actions

Demonstrating the application of the proposed methodology to the simulation results of the previous section supports the wide applicability of realistic animation of FEM simulations as presented in Figure 13.

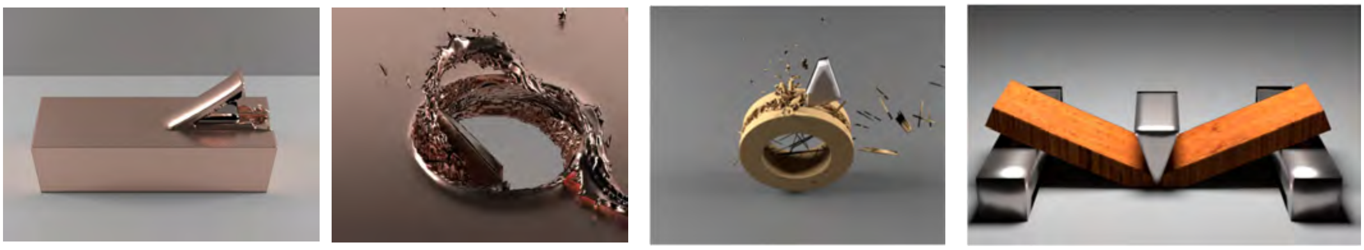


Figure 13. Photorealistic rendering of crafting actions.

5.1.4. Validation of Game Engine-Based Animation

As presented in the proposed methodology, an alternative to FEM-based simulation is the production of animations using the animation capabilities provided by game engines. This is proposed as a workaround in cases where animations do not require the enhanced realism provided by the FEM-based approach or in cases where animations represent simple actions that do not require such an approach. The validation of the feasibility of providing such game engine animation is carried out in this research work through the production of animation for further craft actions directly in the game engine. Examples of such animations for glass formation, wood turning, and clay forming are presented in Figure 14.

Figure 14. Animations for glass formation, wood turning and clay forming.

5.1.5. Equipment Used in Validation

For all the technical experiments in Simulia Abaqus, a desktop computer was used with the following specifications: Intel i7-14700F processor (equipment sourced in Heraklion, Greece), 32 GB RAM, 1 TB M.2 SSD, 2 TB 7200 HDD, NVIDIA RTX 5080 16 GB, and Windows 11 professional operating system. Unity3D and Blender were operated using the same main configuration except for the GPU which was a GeForce RTX 4060 8 GB.

5.2. Expert-Based Evaluation

The evaluation of prototypes was conducted using expert-based approaches by a usability expert and a craft master. Expert-based evaluation is a commonly used method in the HCI field [155]. In cognitive walkthroughs, the evaluator examines the working or non-working prototype, through the eyes of the user, performing typical tasks and identifying areas in the design or the functionality that could potentially cause confusion or user errors [156]. Specifically, in cognitive walkthroughs, the evaluator has a set of questions in mind [157]. Heuristics analysis involves the inspection against a set of 10 usability guidelines [158]. For this study, one usability expert was involved in evaluating the Apprentice Studio and Craft Studio. Furthermore, three craft experts were employed to judge the applicability and perceived usefulness of these tools and improve the readiness of apprentices who exercised using the immersive training toolkit.

5.2.1. Heuristic Evaluation of Apprentice Studio by a Usability Expert

In this section, comments provided by the Usability Expert during the inspection of Apprentice Studio is provided. For the economy of space in our example, only one example per guideline is presented in Table 2.

Table 2. Sample results—heuristic evaluation of Apprentice Studio.

Guideline	Positive	Issue	Suggestion
1. Visibility of System Status	A progress bar is displayed during simulation loading, keeping users informed.	No feedback is provided (if the action was successful) when saving a draft lesson.	Add a confirmation message like "Draft saved successfully".
2. Match Between System and the Real World	Uses real-world terminology, like "blowpipe" and "punty rod", familiar to glassblowers.	Some terms, like "node selection", are technical and not intuitive to craft trainees.	Replace with "Select Tool Part" for better clarity.
3. User Control and Freedom	Users can undo steps during VR tool manipulation.	No "Back" in some menus, forcing users to restart tasks.	Add a persistent "Back" button.
4. Consistency and Standards	Menu layouts are consistent across sections, reducing cognitive load.	Different terminology for similar actions, e.g., "Save Progress" and "Store Progress".	Standardize terminology across all sections.
5. Error Prevention	Prevents users from starting simulations without completing the initial setup.	No warning appears if the user inputs an invalid material property.	Add validation checks with error messages for invalid input.
6. Recognition Rather Than Recall	Frequently used tools are displayed in a toolbar for quick access.	Users must remember shortcut commands for advanced operations.	Provide a visible list of shortcuts in the UI.
7. Flexibility and Efficiency of Use	Advanced users can customize their interface to optimize workflow.	Novices lack a guided walkthrough for their first interaction.	Introduce an onboarding tutorial.
8. Esthetic and Minimalist Design	Clean design with minimal distractions during VR sessions.	Some menus are cluttered with rarely used options.	Hide advanced settings in expandable sections.
9. Help Users Recognize, Diagnose, and Recover from Errors	Provides clear error messages, such as "Invalid Tool Selection".	references during simulation do not suggest corrective actions.	Include step-by-step guidance to resolve issues.
10. Help and Documentation	Includes a searchable help guide.	No embedded tooltips for specific features.	Add context-sensitive tooltips for easier learning.

5.2.2. Heuristic Evaluation of Craft Studio by a Usability Expert

In this section, an exemplary set of comments provided by the Usability Expert during the inspection of the prototype of the Apprentice Studio is provided following the 10 usability guidelines provided above. For the economy of space in our example, only one example per guideline is presented in Table 3.

Table 3. Sample results set for the heuristic evaluation of Craft Studio.

Guideline	Positive	Issue	Suggestion
1. Visibility of System Status	Notifications appear when an action, like assigning a lesson, is completed.	Lack of real-time updates when students submit their work.	Include a dashboard widget to notify educators of new submissions.
2. Match Between System and the Real World	Lessons mimic traditional workflows, aligning with educators' expectations.	Icons for tools (e.g., a wrench for settings) do not always align with their function.	Use universally recognized symbols.
3. User Control and Freedom	Educators can delete or reassign lessons freely.	Lack of confirmation prompts for critical actions.	Add a confirmation dialog for sensitive operations.
4. Consistency and Standards	Same design patterns for creating and assigning lessons.	Inconsistent button colors for similar actions.	Harmonize color schemes for identical actions.
5. Error Prevention	Alerts users before overwriting existing lessons.	Educators can accidentally assign lessons incorrectly.	Include a confirmation step to verify the class.
6. Recognition Rather Than Recall	Educators can browse pre-designed lesson templates.	Previous lesson drafts are not accessible for reuse.	Include a "Recent Drafts" section.
7. Flexibility and Efficiency of Use	Educators can use to make multiple student assignments.	Lack of keyboard shortcuts for common actions.	Add shortcuts for tasks like "Create Lesson".
8. Esthetic and Minimalist Design	Uses a straightforward interface for assigning lessons.	Overuse of different font styles can overwhelm users.	Streamline fonts for a cohesive design.

Table 3. *Cont.*

Guideline	Positive	Issue	Suggestion
9. Help Users Recognize, Diagnose, and Recover from Errors	Notifications explain why an assignment failed (e.g., "Student list not selected").	Error messages sometimes lack specificity (e.g., "Input error").	Make error messages more detailed.
10. Help and Documentation	Offers video tutorials for educators.	Limited guidance on troubleshooting technical issues.	Expand help with a troubleshooting section.

5.2.3. Result of Expert-Based Evaluation from Craft Expert

Three craft experts evaluated the proposed tools, focusing on their applicability within CERFAV's curriculum, perceived usefulness, and impact on apprentice readiness. This preliminary evaluation, conducted before user-based testing, involved a remote demonstration session followed by an open discussion.

Applicability to CERFAV Curriculum: Experts found the tools aligned with CERFAV's learning objectives, particularly in simulating material properties and tool use. The tools were seen as bridging the gap between theory and practice, though concerns were raised about integrating them into an already dense curriculum. One expert noted, "While promising, the onboarding process for educators might require additional training time to achieve full integration". They also suggested customization options for advanced techniques like glass shaping and color application.

Perceived Usefulness: Experts praised the ability to visualize crafting processes in 3D and VR. One participant remarked, "It is remarkable to see how accurately the tools replicate the glassblowing process, especially for understanding the effect of heat and rotation on the material". They agreed that the tools would benefit novice learners, reducing intimidation when transitioning to hands-on practice. A recommendation was made to add guided tutorials for specific techniques like gathering molten glass.

Readiness Levels: Experts anticipated improved readiness among apprentices using the immersive tools before workshop activities. One expert stated, "Students who will practice in VR are likely to show a better understanding of tool handling and process sequences, reducing their hesitations in the physical workshop". They believed the tools would familiarize apprentices with materials and procedures, reducing cognitive load. However, some questioned how well VR training translates to the tactile nuances of working with molten glass.

General Observations: Experts appreciated the potential for remote training, especially when workshop access is limited. While they found the tools easy to navigate, they suggested improving responsiveness and realism in VR tool manipulation. A recommendation was made to enhance haptic feedback for more authentic resistance and interactions.

Conclusion: Experts were optimistic about the tools' potential to enhance craft education but emphasized the need for curriculum-specific refinements, better onboarding for educators, and increased realism. These insights will inform future improvements and user-based evaluations.

5.3. User-Based Evaluation

In this work, we have applied the preliminary user-based evaluation method on a sample of the application suitable for use in the glassblowing training case involving domain experts from CERFAV who were responsible for evaluating with students of their training program. The design of the experiment involved the introduction of a training subject namely "Picking Glass from the Furnace" to a group of ten students using the implementation of the scenario in the Apprentice Studio. CERFAV is a training institution that receives apprentices of various ages depending on the type of training activity they participate. We tried to have a representative sample from all age groups with a distribution of five out of ten of our students in the age group of 18–22, three in the age group 22–25 and two in the group 25–30.

Then, after the introductions, the students were introduced to the same scenario in the workshop. Two questionnaires were created, one to collect feedback from the students and another to collect feedback from the glass masters. The first target was to assess whether the students found the introductory sessions that they had using the apprentice studio sufficient for moving to the introduction at the workshop and whether they found difficulties using or understanding the tools. The second regards the assessment from the glass masters concerning their students' level of preparation using digital tools. In the questionnaire, we used a climax from one to five with one being the smallest and five the highest grade. Grade numbers are accompanied by a literal that provides further assistance to grading such as not sufficient (1), moderately sufficient (3), very sufficient (5), etc. The structure of the questionnaire for students and teachers is presented in Tables 4 and 5, respectively. Feedback from glass educators was also collected via informal interviews with after the completion of the evaluation. Questionnaires were sent back for further analysis. Regarding the sample of educators, three out of five were in the age group of 30–40 while two out of five were more experienced glass blowers in the age group 40–50.

5.3.1. Equipment Used in Evaluation

Regarding the equipment used for the evaluation, this mostly involved mainstream computing equipment. Our setup was two personal computers with an Intel i7 10th generation processor, 16 GB RAM, 512 GB SSD, an NVIDIA 1050 graphics card, and two 24-inch monitors. These specifications were more than adequate for the requirements of the experiment. For the 3D part, the same equipment was used. For the VR part of the evaluation, the two Meta Quest 2 devices were used together with two sets of controllers. The VR training experiences were loaded onto the internal storage of the device and then ran in standalone mode.

Table 4. Structure of the questionnaire for students.

#	Question	Type
Section 1—Orientation		
1.1	On a scale of one to five, please provide a rating on computer usage expertise.	(1–5)
1.2	Do you own a smartphone?	(Y/N)
1.3	Do you access the internet from a phone or computer?	(Y/N)
1.4	If yes, are you using the internet for information and learning about your craft?	(Y/N)
1.5	Is this your first time using digital tools for Craft Education?	(Y/N)
1.5.1	If not, please describe the tools you have used in the past.	Text
Section 2—Apprentice Studio		
2.1	How was your first experience with Apprentice Studio?	(1–5)
2.2	Did you find it easy to browse through the facilities of Apprentice Studio?	(1–5)
2.3	Were all the information and functions easy to locate and understand?	(1–5)
2.4	Did you experience any problems performing actions in Apprentice Studio?	(1–5)
2.5	Did you locate any mismatches in terminology used in class with that of Apprentice Studio?	(1–5)
2.6	Overall, are you happy with what you have experienced using Apprentice Studio?	(1–5)
2.7	Are there any comments you would like to share to help improve Apprentice studio?	Text

Table 4. *Cont.*

#	Question	Type
Section 3—Interaction and Immersion		
3.1	Please rate your 3D experience (computer screen and mouse)	(1–5)
3.1.1	- rate your experience on navigating in the VR environment	(1–5)
3.1.2	- rate your experience in locating information in the VR environment	(1–5)
3.1.3	- rate your experience in locating and grabbing tools	(1–5)
3.1.4	- rate your experience with the manipulation of tools	(1–5)
3.1.5	- rate the level of immersion you achieved in the virtual world in 3D	(1–5)
3.2	Provide comments and suggestions on your 3D experience	Text
3.3	Please rate your overall VR experience	(1–5)
3.3.1	- rate your experience on navigating in the VR environment	(1–5)
3.3.2	- rate your experience in locating information in the VR environment	(1–5)
3.3.3	- rate your experience in locating and grabbing tools	(1–5)
3.3.4	- rate your experience with the manipulation of tools	(1–5)
3.3.5	- rate the level of immersion you achieved in the virtual world in 3D	(1–5)
3.4	Provide comments and suggestions on your VR experience	Text
3.5	Are there any other comments you would like to share?	Text

Table 5. Structure of the questionnaire for teachers.

#	Question	Type
Section 1—Orientation		
1.1	On a scale of one to five, please provide a rating on computer usage expertise.	(1–5)
1.2	Do you own a smartphone?	(Y/N)
1.3	Do you access the internet from a phone or computer?	(Y/N)
1.4	If yes, are you using the internet for information and learning about your craft?	(Y/N)
1.5	For how long have you been educating/training students in the Glassblowing craft?	(Y/N)
1.6	Is this your first time using digital tools for Craft Education?	(Y/N)
1.6.1	- if not, please describe the tools you have used in the past.	Text
Section 2—Craft Studio		
2.1	How was your first experience with Craft Studio? (1–5)	(1–5)
2.2	Did you find it easy to browse through the facilities of the Craft Studio (1–5)	(1–5)
2.3	Were all the information and functions easy to locate and understand? (1–5)	(1–5)
2.4	Did you experience any problems performing actions in the Craft Studio (1–5)	(1–5)
2.5	Did you locate any mismatches in the terminology used in class with that of the Craft Studio? (1–5)	(1–5)
2.6	Did you find it easy to administer your lessons and assign students?	
2.7	Did you find it easy to author simple lessons in the Craft Studio?	
2.8	Did you find it easy to assign lessons to students?	
Section 3—Student Observation		
3.1	Judge the attitude of the students towards the integration of digital technologies in craft training.	(1–5)
3.2	Judge the attitude of your colleagues towards the integration of digital technologies in training.	(1–5)
3.3	Based on your expertise, judge the technologies provided in terms of	
3.3.1	- Efficiency 3.3.3 - Understandability 3.3.5 - Accessibility	(1–5)
3.3.2	- Learnability 3.3.4 - Scalability	(1–5)
3.4	Rate the improvement achieved in students' understanding of basic concepts.	(1–5)
3.5	Rate the improvement in the readiness of students moving from digital to the physical workshop.	(1–5)

5.3.2. Students' Evaluation Results

Section 1: Orientation: Regarding Q1.1 (Computer Usage Expertise), the mean rating was 3.6, with a distribution of two students rating themselves as "1" (novice), three as "3", (moderate), and five as "5" (expert). While half of the students are proficient in computer usage, 20% lack digital literacy, which may affect their ability to use digital tools effectively. Regarding smartphone ownership, in Q1.2 nine students own a smartphone, and one does not. Thus, the majority of students have access to mobile technology, an advantage for digital tool integration. Q1.3 and Q1.4 on Internet Usage showed that all nine smartphone owners accessed the internet and seven of them declared that they were using it for craft learning. Regarding the usage of Digital tools for Craft Education (Q1.5), six students indicated this was their first time, and four had prior experience. Students with prior expertise responded in Q1.5.1 that the previous tools they were familiar with were YouTube, online forums, and video tutorials. One of them mentioned using Computer Aided Design and 3D modeling software for design visualization.

Section 2: Apprentice Studio: Regarding the first acquaintance with Apprentice Studio in Q2.1., it received a mean rating of 4.3 with six students providing a rating of "4", and four students providing a rating of "5". Initial impressions of the Apprentice Studio were very positive. In Q2.2 and Q2.3 that rate the ease of browsing, it received a mean rating of 3.9, with most of the users finding navigation relatively intuitive, but some encountered minor difficulties which were also noted by the experiment operators recording their observations. Regarding problems when performing actions measured through Q2.4 and Q2.5, it received a mean rating of 2.7 with a few participants reporting specific challenges in performing actions, likely due to unfamiliarity with the platform and with minor interface design issues that were spotted by the experiment observatory. Finally, on overall satisfaction it received a mean rating of 4.5, despite the minor usability issues, satisfaction with the overall experience was high.

Free text comments included suggestions for clearer labels on buttons and a request for a tutorial or guide for first-time users. Overall, there was positive feedback on the intuitive design of major features. An exemplary quote follows: "The tool is intuitive, but it took me some time to understand since there were minor issues with the terminology. Further analysis of the craft to align the terminology would be helpful".

Section 3: Interaction and Immersion: Regarding 3D experience, the software received a mean rating on Navigation: 4.0, Locating information: 3.8, Locating tools: 3.6, Manipulating tools: 3.5, and Immersion: 3. Overall, 3D interaction via screen and mouse was well-received, but locating and manipulating tools require refinement. Furthermore, as expected, the users reported medium immersion. Indicative free text comments on the 3D Experience: "It was easy to navigate but harder to grab tools", "The 3D view is clear, but rotating objects felt a bit clunky".

Regarding the VR experience, the software received a mean rating of Navigation: 4.1, Locating information: 4, Locating tools: 4.1, Manipulating tools: 3.6, and Immersion: 4.6. VR outperformed 3D in navigation and immersion while receiving almost common ratings on tool manipulation. Overall based on the observations in 3D users had issues with the mapping of mouse action in the 3D environment while in VR issues related to getting to know how to use the VR controllers. Indicative free text comments on the VR Experience: "Navigating in VR felt very natural", "Grabbing tools in VR was better than in 3D, but there is room for improvement in precision". The results are graphically visualized in Figure 15.

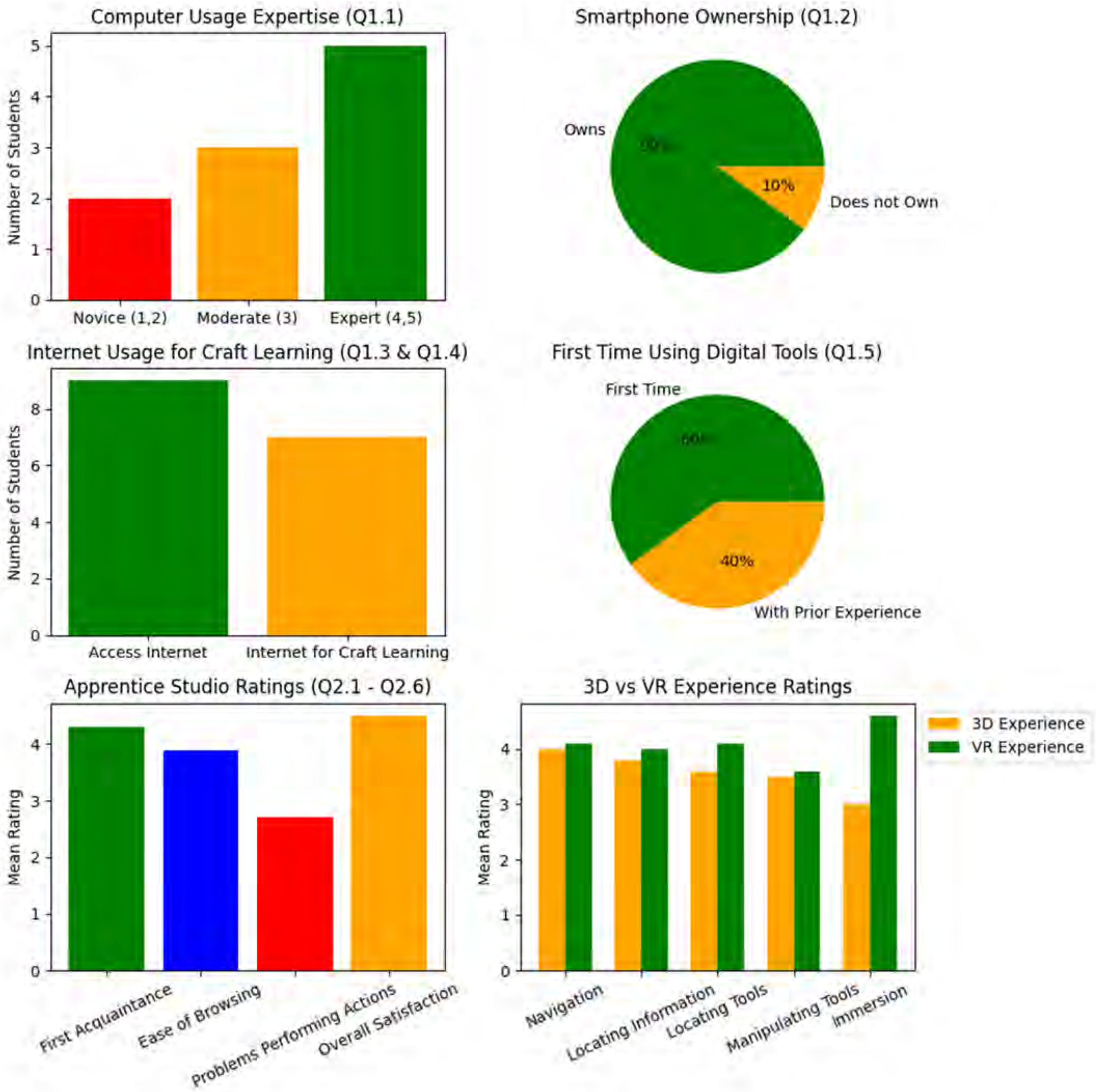


Figure 15. Analysis of the students' evaluation results.

Additional comments: Regarding additional comments, many students noted the potential for expanding the library of craft-related VR simulations. For example, one of the comments received was "Adding more VR scenarios for different crafts would make this tool invaluable".

The overall insights into the effectiveness can be summarized as follows. Both Apprentice Studio and VR simulations show strong potential for improving craft education, with participants expressing high satisfaction overall. VR offers significantly better immersion and interaction than traditional 3D interfaces without the latter being useless since they provide a cost-effective way to craft training. Regarding challenges, interface usability, especially in 3D interactions, needs improvement to lower the learning curve since some students struggle with technical jargon and navigation. Regarding recommendations for improvement, including a step-by-step tutorial or user guide for new users would be well received. Furthermore, enhancing tool manipulation mechanics, especially in the 3D mode, is considered important. Last but not least, aligning glossary with craft-specific terminology was noted as important. Regarding Future Research Directions, exploring scalability by incorporating additional crafts and testing with a larger participant pool.

Students' results synthesis: The responses from participants provide valuable insights into their experiences with digital tools, usability challenges, and the effectiveness of both 3D and VR environments for craft education. While individual perspectives varied, there were some common themes. Participants had mixed levels of digital literacy, highlighting concerns about the learning curve required to engage effectively with digital platforms. Although nearly all participants owned smartphones and accessed the internet, their use of digital resources for craft education varied. Several participants with prior experience mentioned relying on platforms like YouTube or forums for learning, indicating that while they were familiar with digital content consumption, structured digital training was new to many.

Initial impressions of the Apprentice Studio were generally positive. Participants appreciated its intuitive design but noted that it took some time to become fully comfortable with the platform. Some described their first experience as “smooth and engaging”, while others found navigating through the features slightly challenging. A recurring theme was the difficulty in aligning terminology within the Apprentice Studio to traditional craft education, with some expressing frustration over inconsistencies that made certain features harder to understand.

Participants also suggested that a guided tutorial or onboarding process would have made their experience easier, with one noting, “The tool is intuitive, but at first, I struggled with some of the terminology. A short tutorial or glossary would help new users a lot”. Despite these minor obstacles, the general sentiment was that the tool had strong potential, and most felt comfortable using it after some initial exploration.

The contrast between 3D and VR experiences was evident in participant feedback. While some participants found the 3D interface sufficient for their needs, others struggled with certain interactions, particularly manipulating tools. One participant stated, “It was easy to navigate but harder to grab tools”, suggesting that while movement felt natural, interaction needed refinement. Another noted, “The 3D view is clear, but rotating objects felt a bit clunky”. In contrast, the VR environment was widely praised for its immersive nature. Many participants described their VR experience as “engaging” and “more realistic” compared to traditional 3D interfaces. Some appreciated how “Navigating in VR felt very natural”, while others found grabbing tools in VR significantly better than in 3D but still identified areas for improvement, such as precision in interactions. A recurring theme was that VR felt more intuitive for hands-on tasks but required some initial adaptation to the controllers.

Participants expressed enthusiasm about the potential of these digital tools for craft education. Many saw the VR component as particularly valuable and believed it could significantly enhance traditional learning methods. Several participants suggested expanding the range of VR scenarios to cover more crafts, with one stating, “Adding more VR scenarios for different crafts would make this tool invaluable”. While usability concerns were present—particularly in 3D interactions—most participants felt that with some refinements, these tools could become essential resources for craft training. Many emphasized the importance of providing better onboarding support, improving tool interaction mechanics, and ensuring terminology aligns with traditional craft training.

Looking forward, participants suggested that future improvements should focus on enhancing user-friendliness, increasing accessibility, and ensuring that digital tools integrate seamlessly into existing craft education practices. Many were excited about the potential of these tools and believed they could be even more impactful with continued development and expansion.

5.3.3. Educators' Evaluation Results

Section 1: Orientation: Q1.1 (Computer Usage Expertise) received a mean rating of 4.0 with a distribution of two educators rated themselves "5" (expert), two as "4", (very proficient), and one as "3". In Q1.2 (Smartphone Ownership), all five educators own a smartphone, highlighting a foundation for leveraging mobile technologies in education. In Q1.3 (Internet Usage), all five educators access the internet from their phones or computers, and four use it for craft-related information or learning. Most educators are comfortable with using the internet for professional growth and can adapt to online craft tools. In Q1.4 (Use of the Internet for Information on Craft), most educators already use the Internet to learn about their craft, showing a high level of openness to digital resources. However, one educator might require additional support or motivation. In Q1.5 (Experience in Educating Glassblowing), two educators reported more than ten years of experience and two reported 5–10 years and one less than 5 years. The participant group has diverse experience levels, which may affect their adoption of digital tools. The results of Q1.6 (First Time Using Digital Tools for Craft Education) indicate that three educators are using digital tools for the first time, while two have prior experience including experience in VR. The tools used include video tutorials, CAD software, and AR and VR applications. While some educators are already familiar with digital tools, the majority are new to structured digital craft education platforms. Overall, CAD software was praised for its design precision and the video tutorials were noted for their accessibility.

Section 2: Craft Studio: In Q2.1 (First Acquaintance with Craft Studio), the Craft Studio received a mean rating of 4.4 with three educators rating it "5", and two rated it "4", thus, allowing the assumption that the initial impressions of the Craft Studio are very positive. Regarding Q2.2 (Ease of Browsing), the Craft Studio received a mean rating of 3.8 since most educators found browsing straightforward, but some encountered minor navigation challenges. The rating was very close to the one achieved by the Apprentice Studio in a similar question. In Q2.3 (Information Easy To Understand), it received a mean rating of 4.1 since most educators found information easy to understand. In Q2.4 (Problems Performing Actions), the Craft Studio received a rating of 2.6. since some educators experienced difficulties in executing certain actions, likely due to unfamiliarity with the interface and due to some terminology mismaps. This was also highlighted in Q2.5 (Mismatches in terminology) where a rating of 3.1 was received. In Q2.6 to Q2.8 (Lesson Administration and Assignment), regarding lesson administration, Craft Studio received a rating of 4.0, regarding the authoring of lessons, a rating of 3.8, and regarding the ease of assigning, a rating of 4.2. Overall, educators found the tools effective, though authoring presented slightly more difficulty due to the issues described in Q2.4. Finally, in Q2.6–Q2.8 (Suggestions for Lesson Administration), several comments were received such as "It would be helpful to have pre-designed lesson templates", and "The lesson assignment process is intuitive, but the authoring interface could be more flexible".

Section 3: Observation of students: In Q3.1 (Student Attitude Towards Digital Technologies): Regarding students' attitude through digital technology, it was rated 4.6 since educators perceived a strong positive attitude among students towards digital integration in craft training. In Q3.2 (Colleague Attitude Towards Digital Technologies), a score of 3.8 indicated that, while colleagues are generally supportive, there may be some hesitancy or skepticism. In terms of technology evaluation Q3.3, the proposed approach scored 4.4. for Efficiency, 4.2 for Learnability, 4 for Understandability, 4.2 for Scalability, and 4.6 for accessibility. The provided technologies are rated highly across all dimensions, with accessibility being the strongest aspect empowered due to the alternative forms of performing the education (3D and VR) which makes it easier for people with different characteristics to select their preferred training style. In Q3.4, educators observed a significant improvement in students' understanding of craft concepts through the use of the tools providing a rating of 4.5. Finally, in Q3.5 (Improvement in Readiness for Physical Workshops) a complementary to the Q3.4 finding was the 4.3 rating indicating that educators believe that digital tools effectively prepare students for hands-on training in physical workshops.

Free text comments on Q3.4 and Q3.5 include "Students seem more confident in approaching tasks after practicing digitally", and "The transition to the workshop was smoother, but the physical nuances of glassblowing still require hands-on exposure".

The results are graphically visualized in Figures 16 and 17.

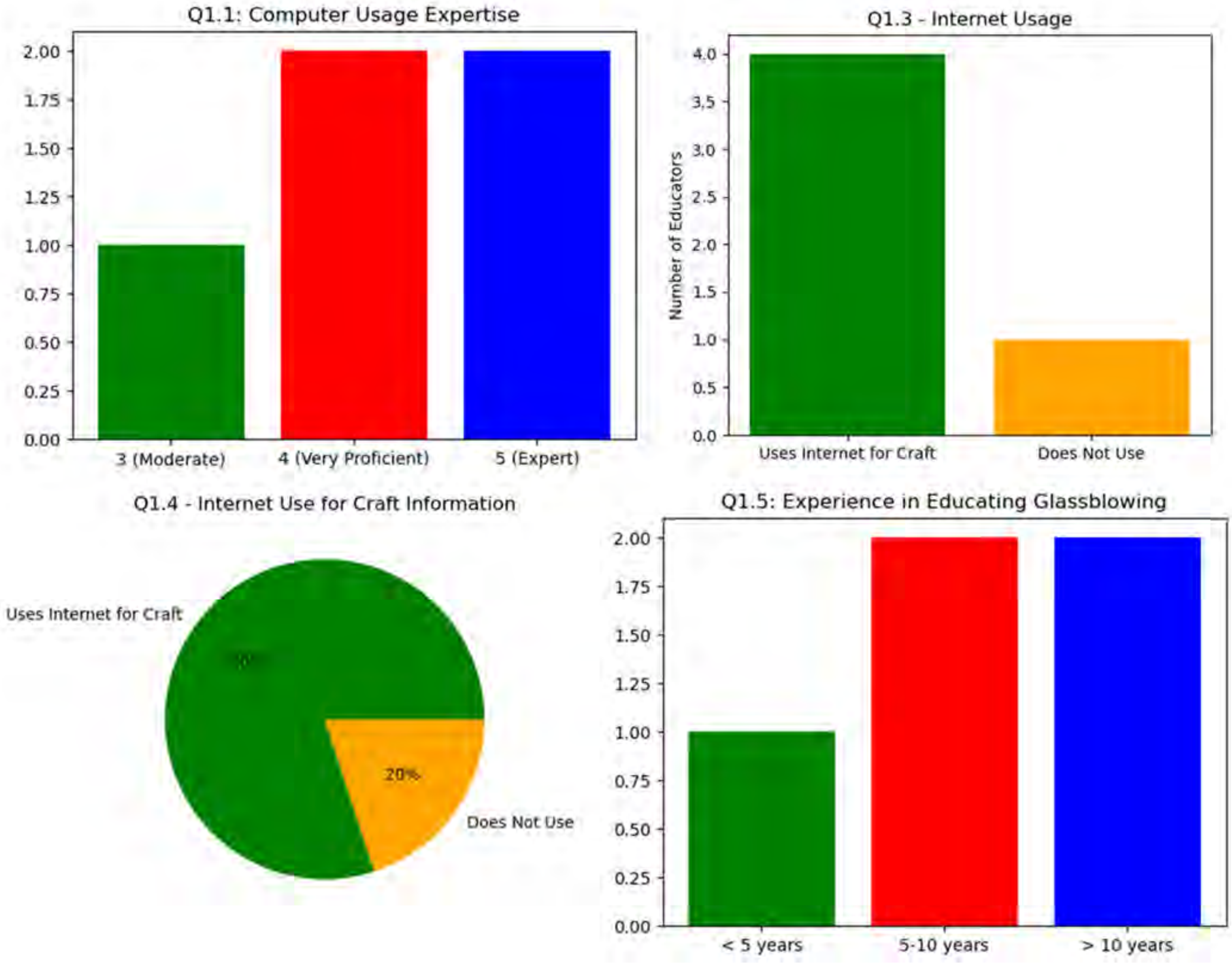


Figure 16. Analysis of the teachers' evaluation results (Q1–Q5).

Additional comments and overall insights: Overall, in terms of effectiveness, the Craft Studio and associated tools are highly effective in enhancing students' understanding and readiness for hands-on workshops. Minor usability issues in authoring lessons and interface navigation were highlighted while it is assumed that there is room to improve interactivity and collaboration features. In terms of recommendations, the introduction of pre-designed templates for lessons authoring the expansion of the craft simulation library, and the addition of collaborative tools are considered the most constructive ones. Future research investigating the impact of long-term use on both educators and students should be explored together with a wider user-based evaluation with larger educator and student cohorts.

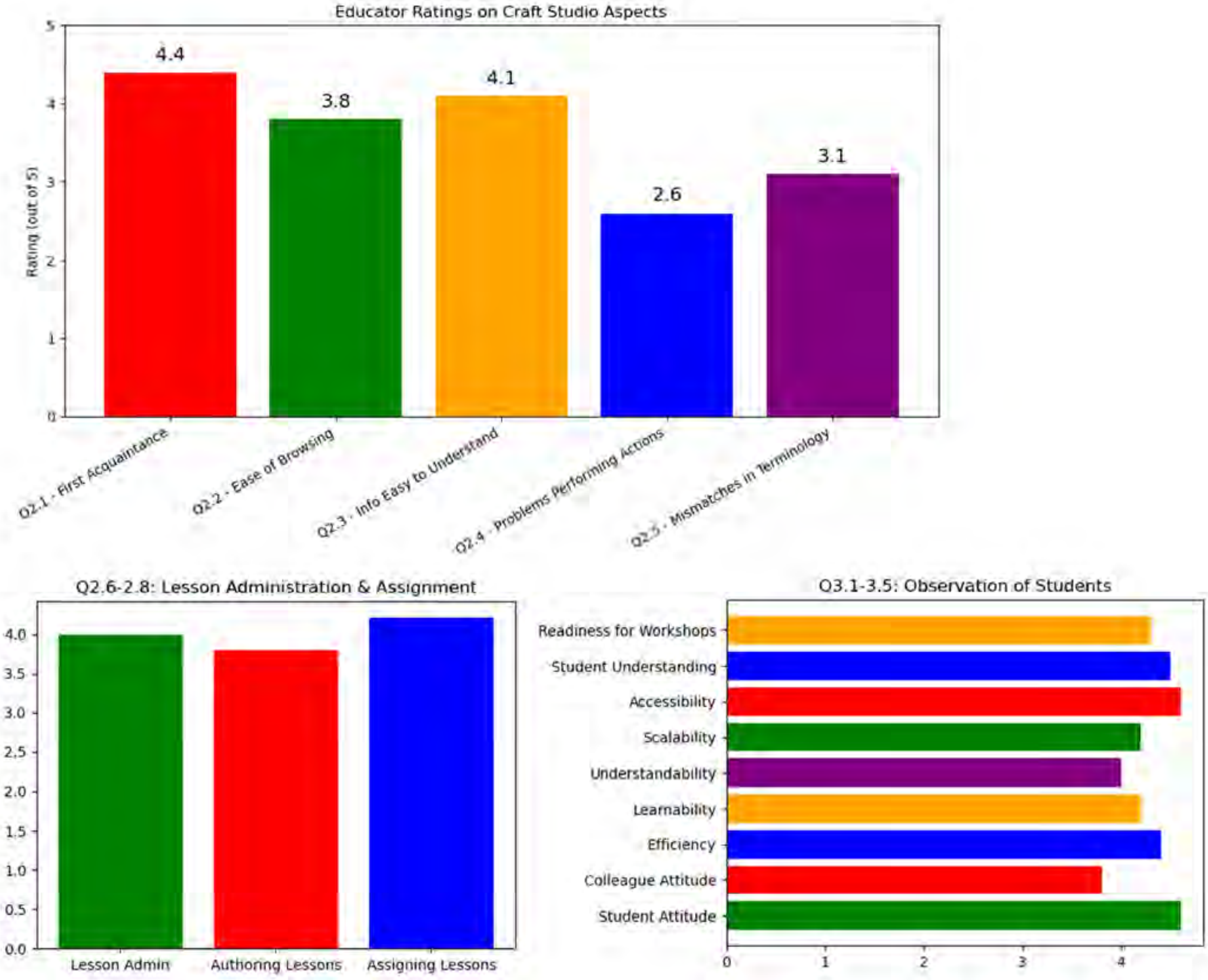


Figure 17. Analysis of the teachers' evaluation results (Q2.1–2.8 and Q1.3–3.5).

Synthesis of educators' results: The educators who participated in the experiment generally displayed high levels of digital literacy. Most felt confident in using computers and digital tools, which suggests they can engage effectively with technology in their teaching. While all educators owned smartphones and regularly accessed the internet, one educator admitted to not frequently using online resources for learning about their craft, suggesting a need for additional support or motivation in digital adoption. In terms of experience, participants represented a diverse range, from those with over a decade of teaching experience to those with less than five years. This diversity led to varying perspectives on digital tool integration—some saw them as a natural evolution, while others viewed them as an adjustment requiring effort. For the majority, using digital tools for craft education was a new experience. Those who had prior exposure highlighted the usefulness of CAD software and video tutorials, particularly for precision and accessibility. However, they noted a lack of interactivity in traditional digital resources, which they hoped new tools like Craft Studio could address.

Educators expressed highly positive first impressions of the Craft Studio, with many praising its potential for structured digital craft education. Navigation was generally smooth, though some encountered minor challenges in browsing, suggesting that a more intuitive design could further enhance usability. Most educators found the information provided within the platform clear and well-organized. Despite the strong initial reception, some educators encountered difficulties performing certain actions. A few struggled with unfamiliar terminology, pointing out mismatches between the language used in digital tools and the vocabulary they commonly use in class. This misalignment sometimes led to confusion, reinforcing the need for better alignment between the platform's terminology and traditional craft instruction. When it came to lesson administration, educators found assigning and managing lessons straightforward. However, creating lessons proved slightly more challenging. Some expressed a desire for pre-designed templates to streamline the authoring process, while others emphasized the need for more flexibility in customizing lessons. One educator remarked that while the assignment process was intuitive, lesson creation required additional effort to be truly effective.

Educators observed that students were overwhelmingly positive about integrating digital tools into craft education. Many noted increased enthusiasm and engagement, with students appearing more confident after practicing digitally before moving to physical workshops. However, educators emphasized that while digital tools are beneficial for concept comprehension and practice, hands-on exposure remains crucial for mastering the physical nuances of glassblowing. Among colleagues, there was a mix of enthusiasm and hesitation. Some educators noted resistance among peers who were accustomed to traditional teaching methods, while others observed a growing interest in digital integration. This variation suggests that while the sector is evolving, continued support and demonstration of digital tools' benefits may be needed to encourage broader adoption. In evaluating the technology itself, educators appreciated its accessibility and flexibility, particularly the availability of both 3D and VR options, which allowed users to choose the mode that best suited their learning style. Some noted that the digital platform effectively prepared students for hands-on work, though they acknowledged that physical skills still require in-person refinement. One educator commented that students seemed more confident in approaching tasks digitally, but the real challenge lay in translating that confidence into physical craftsmanship.

Educators largely viewed the Craft Studio as a valuable tool for enhancing both understanding and readiness for hands-on craft training. They acknowledged minor usability challenges, particularly in lesson authoring and navigation, but felt these issues could be addressed with improvements such as pre-designed templates and refined user guidance. One recurring theme was the potential for expanding the digital craft education ecosystem. Many educators suggested incorporating more craft-specific simulations and collaboration tools to enhance interactivity. Overall, the findings highlight strong support for digital tool adoption in craft education, with a few areas for improvement to ensure a seamless and effective integration into existing teaching practices.

6. Discussion

This study introduces a novel methodology for simulating and immersive training traditional craft processes, addressing key limitations of conventional and prior digital approaches. The methodology enhances effectiveness, scalability, and accessibility.

6.1. Advances Concerning Traditional Training

Traditional training relies on observational learning or apprenticeship, which, while effective, is resource-intensive and geographically constrained. The proposed approach overcomes these limitations by enabling digital lesson distribution through reusable Action Animators, allowing institutions worldwide to offer standardized training without requiring technical expertise beyond basic computer and VR device use. By integrating

FEM simulations for material-deforming actions and real-time game engine simulations for simpler tasks, the methodology bridges the gap between theory and practice. Traditional training methods, while effective, are resource-intensive [159,160], with scalability issues particularly in manual dexterity-based fields [161]. VR-based craft training has been shown to enhance skill acquisition while reducing material waste [66,162,163], with FEM simulations further improving conceptual understanding and reducing cognitive overload [149].

The methodology fosters deeper understanding by enabling users to explore scientific principles alongside practical execution. Digital environments eliminate safety risks, allowing learners to focus on principles without concerns about injuries or wasted resources. Real-time feedback mechanisms provide quantitative performance metrics, allowing iterative skill improvement. The ability to repeatedly practice complex tasks, such as attaching a glass handle, without resource waste enhances learning efficiency. Educators and students in user studies highlighted the cost-effectiveness of this approach for familiarization before workshop practice. A non-VR version enables remote training, expanding accessibility. Institutions like CERFAV benefit from reduced resource consumption, aligning with eco-friendly policies. However, haptic feedback in controllers remains insufficient for high-precision craft training.

6.2. Technical Advances

The methodology employs high-fidelity FEM simulations and game engine-based kinematics to replicate crafting actions. FEM models are reusable across various craft contexts, ensuring broad applicability and the validation process confirmed that simulation data can be translated into high-quality pre-rendered simulations. These simulations provide realism, allowing learners to engage with accurate representations of tools and materials without physical resources. Advanced FEM techniques surpass earlier material-deforming modeling methods with high scientific precision [150,151]. They enable a detailed understanding of craft processes, including deformation and stress distribution [152], whereas prior systems relied on simplified animations [153]. Real-time FEM visualization further enhances training environments, ensuring accuracy and pedagogical effectiveness.

The Dual Simulation Framework optimizes computational resources by combining FEM for complex material interactions (e.g., chiseling wood) with game engine simulations for simpler operations (e.g., rotating a glassblowing rod). The modular Action Animator components enhance flexibility, contrasting with less adaptable previous solutions. The streamlined integration pipeline involving Blender and Unity improves realism through photorealistic enhancements. The system supports various input devices, improving accessibility compared to past approaches.

Previous digital craft education efforts focused on eLearning platforms [164,165], or rudimentary interactive applications which lacked real-time adaptability [166]. FEM-based simulations dynamically replicate craft processes, aligning with digital twin technology [167]. Reusable Action Animators extend modular frameworks explored in game-based learning [168], enhancing their application in craft preservation.

This methodology improves effectiveness, scalability, and accessibility. High-fidelity simulations enhance engagement and retention. Study and examination modes provide iterative feedback, enabling mastery of both procedural accuracy and underlying principles. Digital tools and modular lesson specifications ensure global distribution, overcoming traditional training's resource constraints. Unlike prior systems, this methodology supports a broad range of hardware configurations, ensuring accessibility even in resource-limited regions. Action Animators allow tailored training, further increasing inclusivity.

The methodology is part of a broader framework supporting heritage craft education, informed by Cognitive Load Theory [149]. It integrates online facilities with multimodal immersive training tools adaptable to user expertise and equipment. The Craeft Online Training platform [169] will provide free access to the infrastructure.

6.3. Contribution to the Preservation of Intangible Cultural Heritage

Traditional crafts, integral to intangible cultural heritage, face threats due to declining practitioners and limited documentation. Digital archives capturing tools, materials, and actions ensure long-term preservation and facilitate education and research.

Digital technology's role in heritage preservation is well-documented [170]. Virtual reconstructions engage wider audiences and ensure knowledge transmission [171], but many focus on artifact representation rather than skill transfer [172]. The proposed methodology bridges this gap by capturing procedural knowledge, aligning with embodied learning principles [173,174].

This approach democratizes craft training, enabling global participation regardless of location or resources. By eliminating traditional apprenticeship barriers, such as proximity to skilled mentors and material access, it supports broad engagement with traditional crafts.

6.4. Theoretical Implications

This methodology represents a paradigm shift in craft education, blending theoretical understanding, practical execution, and digital interaction. Immersive learning enhances situated learning [175] and bridges gaps between declarative and procedural knowledge acquisition [176]. The adaptive training model aligns with constructivist pedagogical principles [177] and supports cognitive apprenticeship frameworks [178], reinforcing guided exploration's effectiveness in skill-based disciplines.

Additionally, this methodology aligns with contemporary trends in gamification, VR-based training, and remote learning. It balances modern pedagogy with traditional craft preservation, emphasizing adaptability and precision in digital heritage tools.

6.5. Limitations

Despite its advantages, the methodology has limitations. While scalable, expanding the collection of craft actions requires additional simulations, necessitating technical expertise. However, the methodology ensures the seamless integration of new actions via Action Animators. Another limitation is the absence of semantic process representation, which could facilitate automatic lesson generation. Ongoing work aims to address this issue and further enhance scalability. Lastly, the pilot-stage implementation requires broader validation across more crafts and educational contexts. Large-scale user studies will provide further insights into its effectiveness across diverse training scenarios.

7. Conclusions and Future Work

This study presents a methodology for immersive craft training using FEM-generated animations. Crafting processes are challenging to simulate realistically, but integrating FEM results into VR environments offers an innovative solution. This approach enhances training by accurately replicating material behaviors, such as deformation and stress distribution, creating a learning experience close to real-world conditions. A key contribution is overcoming the limitations of real-time physics simulations by leveraging precomputed FEM data. While this ensures high-fidelity simulations, it also necessitates pre-simulated outputs, limiting real-time adaptability. To address this, we introduced Animation Sequences and Action Animators, enabling the reuse of precomputed actions across training scenarios. This structured framework enhances scalability, allowing simulations to be refined in Blender and integrated into Unity for photorealistic environments.

To ensure usability for craft educators and students, the methodology separates lesson creation and execution through Craft Studio and Apprentice Studio. Instructors can design immersive lessons using Action Animators, while students practice skills in VR environments. The study and examination mode further supports iterative learning, bridging virtual training with hands-on experience.

While this work demonstrates strong potential, several areas for improvement remain. From a technical perspective, optimizing FEM simulations is crucial to support real-time applications. Methods for accelerating FEM calculations could help address this challenge. Additionally, improving haptic feedback would enhance the realism of material interactions, allowing users to better perceive the texture and resistance of crafting materials. Advancements in photorealistic rendering, such as real-time ray tracing and physically based rendering, could further enhance the training environment. From an educational perspective, large-scale evaluation is necessary to validate the effectiveness of the proposed methodology. Expanding this study to include more craft would provide further insights. Additionally, evaluating the approach within traditional apprenticeship contexts could offer a deeper understanding of its impact. A formal evaluation incorporating more craft practices is already planned as part of future work.

Further improvements in the technical aspects of the methodology will also influence the assessment strategies used. Future research should explore how the integration of advanced technical components affects learning outcomes, particularly in terms of user engagement, motivation, and skill retention. As VR technologies continue to evolve, immersive training systems have the potential to transform skill-based education across multiple domains, fundamentally changing the way hands-on training is delivered and experienced.

Author Contributions: Conceptualization, N.P. and X.Z.; methodology, N.P., X.Z., D.Z., A.D. and I.M.; software, N.P., X.Z., D.Z., N.N., P.F., A.S. and I.D.; validation, N.P. and X.Z.; formal analysis, N.P., X.Z., D.Z., A.D., N.N., P.F., I.D. and I.M.; investigation, N.P., X.Z., D.Z., A.D., N.N., P.F., I.D., D.A., P.H., N.C. and I.M.; resources, N.P., X.Z., D.Z., A.D., D.A., P.H., N.C. and I.M.; data curation, N.P., X.Z., D.Z., A.D. and I.M.; writing—original draft preparation, N.P.; writing—review and editing, N.P., X.Z., D.Z., A.D., N.N., P.F., I.D., A.S., D.A., P.H., N.C., D.A., P.H., N.C. and I.M.; visualization, N.P., X.Z., D.Z., A.D., N.N., P.F., I.D., A.S. and I.M.; supervision, N.P. and X.Z.; project administration, N.P. and X.Z.; funding acquisition, N.P. and X.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was implemented under the project Craeft, which received funding from the European Union's Horizon Europe research and innovation program under grant agreement No. 101094349.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available upon request.

Acknowledgments: The authors would like to thank the anonymous reviewers for contributing to the enhancement of the quality of this manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

3D	Three-Dimensional
AR	Augmented Reality
CFD	Computational Fluid Dynamics
CH	Cultural Heritage

FEA	Finite Element Analysis
FEM	Finite Element Method
HMD	Head Mounted Displays
ICH	Intangible Cultural Heritage
MR	Mixed Reality
SDK	Software Development Kit
TCs	Traditional Crafts
UNESCO	United Nations Educational, Scientific and Cultural Organization
VR	Virtual Reality

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