CRAEFT

care, judgment, dexterity

D2.1. Action and affordance modelling

Project Acronym	Craeft
Project Title	Craft Understanding, Education, Training, and Preservation for Posterity and Prosperity
Project Number	101094349
Deliverable Number	2.1
Deliverable Title	Action and affordance modelling
Work Package	2
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Number of pages	88

This project has received funding from the European Commission, under the Horizon Europe research and innovation programme, Grant Agreement No 101094349.
http://www.craeft.eu/

Executive summary

Section 1 provides an introduction to the purpose and scope of this deliverable in the Craeft project. In addition, it comments on the purpose of each section and provides definitions of concepts used in this deliverable.

Section 2 reviews the literature, software products, and past projects to establish the state-of-the-art simulation of crafting actions. Section 2.1 reviews the theoretical modelling of crafting actions from a cognitive, ontological, and semantic perspective. Next, in Section 2.2, we review simple craft simulators available today. Thereafter, we review craft presentation systems that visualise crafting actions, although not simulators. Section 2.4 reviews the few existing visual simulations for crafts, that is, software that predicts the appearance of craft products. In this context, we also review a rendering system that we intend to use to simulate the appearance of transparent and shiny objects. Section 2.5 reviews the state-of-the-art in producing scientific simulations and, specifically, the Finite Element Method, aimed at mechanical simulations and its application in crafting actions. In the same section, we furthermore review textile modelling software and applications and select one of them as a tool that we will use. In Section 2.6, we review robotic re-enactments of crafting actions because the reproduction of actions by robots implies precise definitions for how they are executed.

In Section 3, we define our approach towards action and affordance modelling and identify the elements of crafting actions that we need to consider in the design of simulations. These are (a) environmental conditions, (b) physical properties of materials, (c) object shape and pose and (d) causing entities (forces, motions). These elements are modelled to have a state that varies over time. Object shapes are modelled in a volumetric mesh (tetrahedra or hexahedra), and the rest are physical quantities in the SI system.

Actions are classified under four classes, (1) additive, (2) subtractive, (3) interlocking, and (4) shaping actions. The causing entities of actions are identified, and two approaches are chosen to computationally model them: force-oriented and motion-oriented. The first aim is to investigate the force required to achieve an action on a specific material. The second is suited to the re-enactment of actions from motion recordings. Auxiliary actions, namely waiting and moving objects, were identified. All actions were mapped to the Maker-Material-Negotiation model in D2.2.

Affordances are modelled based on the physical properties and behavioural models of materials. Behavioural models determine how materials behave when affected by an object or force and, in our case, regard damage and plasticity models. Given the actions of interest, we corresponded actions of interest to material properties and behavioural models.

Section 4 links this deliverable with D2.2 and specifically the Maker Material Negotiation model, which is there developed. In that section, we identified the ontology of the four action classes in terms of the objects that are created, transformed, or ceased during the (simulated) actions. Furthermore, we identify two auxiliary actions, namely waiting and moving. At the end of this section, we present the action description template that we used to model archetypal actions; each action archetype presented is modelled first by completing this template and next by transcribing the template contents in the definition of an action to be simulated.

In Section 5, we first (in Section 5.1) present our technical approach to simulation, using the Finite Elements Method and its implementation. We define simulation inputs and outputs in a way that they can be integrated with third-party software and, in particular, with the Unity engine which we will use to create training applications for crafts. In Section 5.2, we simulation archetypes are designed so that we can later on instantiate them to craft-specific simulators, by determining the material properties and behavioural models for each case of material. Subclasses of the four generic action classes (add, subtract, shape, and interlock) that correspond to crafting actions of interest were implemented and tested under varying conditions, action parameters, and materials types. For each subclass, the results produced volumetric animated meshes that represent the evolution of the material structure during the action and after it, for elastic materials. Each subclass was also semantically annotated using the Arts and Architecture Thesaurus, so link actions with their verbal descriptions. Finally, in Section 5, we tested the combination of actions into processes, providing three indicative examples. For the reproducibility of the results, we stored the inputs and outputs of these simulations in the Zenodo platform at: https://zenodo.org/records/10567707

In Section 6, we describe how the simulators we create can be exported to software that implements virtual and immersive environments. As the Unity game engine is our implementation tool for these environments, this section describes the technical method of the interface between the Simulia Abaqus outputs and the Unity game engine.

Section 7 concludes this deliverable and outlines the next steps of work.

Document history

Date	Author	Affiliation	Comment
29/1/2024	Xenophon Zabulis	FORTH	First draft of sections 1-5
30/1/2024	Peiman Fallahian Sichani & Laura Werup	Khora	Additions to section 6
5/2/2024	Valentina Bartalesi	CNR	Review
6/2/2024	Xenophon Zabulis	FORTH	Update
28/2/2024	Xenophon Zabulis	FORTH	Update

Abbreviations

CH	Cultural Heritage
FEA	Finite Element Analysis
FEM	Finite Element Method
MoCap	Motion Capture
MR	Mixed Reality
RCI(s)	Representative Craft Instance(s)
VR	Virtual Reality

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1 Introduction

This deliverable aims to deepen our understanding of the workings of a practitioner when creating craft products. The reasons we have to do so stem from our goals to contribute to the education and training of new practitioners, with safety and with conservation of material and energy resources. For this reason, we wish to model crafting actions, so that we can simulate them and create educational and training applications.

The above goal makes a step forward from the work done in the Mingei IA, where we have modelled crafting processes "phenomenologically". That is, in Mingei, our representation was purely descriptive; crafting processes were described in terms of plans (process schemas) and their execution (processes). Tools, materials, and actions were described verbally and associated with images and videos that illustrate them.

In this work, we wish to take a step further and understand the mechanisms that underpin the transformation of materials into craft products. To prove the validity of our understanding we borrow Marr's idea [49] that (in our own words and understanding) says that if you say that you understand an activity you should be able to recreate it.

In this sense, our understanding aims to obtain the potential to be able to electronically recreate the activities of the practitioner and be able to predict the outcomes of practitioner actions. Although in Section 2 we review the robotic implementation of craft actions, our goal is not to train robots but humans. Robotic technologies have a place in the crafts of the future, but only for tedious, unhealthy and menial tasks; not for tasks that involve *"care, judgement, and dexterity"* [20].

As a first step towards this goal, we approach mechanical simulation, which is based on Physics, Materials Sciences, and Mechanical Engineering. This enables us to understand the mechanical actions performed by the practitioner and predict their outcomes, which is useful because we can then develop educational and training tools based on this understanding. This version of the deliverable focuses on this, mechanical understanding. In the next version, we will also focus on the cognitive actions employed by the practitioner, mainly judgement and the way that practitioners make decisions and design products. The goal of mechanical understanding takes us to the real simulation, which is a way to electronically "recreate" crafting actions and, generatively, predict their outcomes. Generatively here means that the outcome of the simulations is not only the induced motions and exerted forces due to practitioner actions, but also the "product" of the action of the practitioner, that is the transformed material(s).

Another goal that Craeft has is generality. That is, besides the simulations we achieve for our Representative Craft Instances (RCIs), we wish to be able to extrapolate our methodology of understanding for virtually all crafts. For this reason, our approach has the following two characteristics:

The analysis of crafting activities into elementary actions.

The modelling of actions using archetypes that capture the mechanical principles but can be instantiated multiple times, for similar materials, tools, and action parameters.

Using this approach, we create a vocabulary of archetypes which can be reused for multiple craft instances, beyond the scope of Craeft. Our initial classification of actions into four categories (Add, Subtract, Transform, Interlock) is refined based on the datasets collected in WP1, where we had the opportunity to observe actions in detail and identify subclasses of these categories. In this deliverable, we provide archetypal simulations for these subclasses.

In Section 2, we review simulations of craft actions and methods that exist in the literature, indicating that there are not many, with an exception being textiles due to the industrialisation of their manufacturing. Our quest to find a way to generically simulate the diverse mechanical actions encountered in crafts led us to Finite Element Analysis (FEA) and Finite Element Methods (FEMs) that enable mechanical engineers to analyse and visualise the behaviour of components and systems in a simulation before physical prototypes are built. Similarly, to our goals, FEMs help engineers in optimising designs, reducing costs, and ensuring that mechanical systems meet performance and safety requirements. FEA software tools are important in facilitating these simulations by providing programmable and user-friendly interfaces, as well as robust solvers for solving the complex sets of equations involved.

In Section 3, we explain our rationale for the modelling of simulations and identify the elements that we need to model to achieve them. Our analysis is guided by Gibson's ideas [16] of modelling decisions and actions, also known as the theory of affordances, which we interpret in the context of tools and material properties.

In Section 4, we provide a link to this deliverable with D2.2 where actions are semantically and ontologically modelled. In this deliverable, we focus on software modelling of the entities transformed, composed, ceased or created, so that we appropriately organise the inputs and outputs of our simulations. As our goal is the understanding of crafting actions, we link actions to their semantic representations.

In Section 5, we present our technical approach towards the implementation of mechanical simulation using FEA and present multiple archetypal simulations that we developed. The simulators developed have been prioritised as to their necessity. Specifically, we did not delve into the simulation of textile manufacturing because this work has been well covered by the industry; thus, for textile modelling, we adopt an open-source simulator (TexGen) that is reviewed in Section 2.

To formulate the proposed approach, we use the following definitions.

We refer to the scene as the workspace where the craft is exercised. Scene elements are the objects in the scene. Scene properties are the environmental properties, such as temperature.

- A tool is an object or body member employed to make use of an affordance it bears [16], e.g., scissors provide the affordance of cutting. A machine is an apparatus comprised of Archimedean Simple Machines. An action is an event that consists of doing something intentionally by some agent of action [50]. An activity is a set of actions carried out by one or more persons. Thus, activities are events. The entities involved in the crafting process are either endurants or perdurants, corresponding to "continuants" and "occurrents" [17] in Basic Formal Ontology, respectively. Endurants are entities which exist in full in every instant at which they exist at all. Perdurants are entities which unfold themselves over time in successive temporal parts or phases.

Endurants are materials, tools, machines, workplaces, and craft products. Perdurants are actions and natural phenomena.

- A crafting process is a set of activities that transform materials into articles of craft. A workflow is an orchestrated and repeatable activity, enabled by the organisation of resources into processes. A crafting process schema is a representative prescription for how a set of activities should operate in a workflow to regularly achieve desired outcomes [18]. To refer to parts of a process schema or process, we say that they are comprised of step schemas and steps, respectively, independently of their depth in the process schema or process.
- Mechanical advantage is a measure of the force amplification achieved by using a tool, mechanical device or machine system [32]. The device trades off input forces against movement to obtain a desired amplification in the output force. The model for this is the law of the lever.
- It is noted that the definitions above are included in D1.1, as part of an “interdisciplinary vocabulary” that we created to facilitate collaboration between partners of different disciplines.

2 Related work

In this section, we review works relevant to the understanding, modelling, and computational simulation of actions in traditional crafts.

2.1 Conceptualisation and Representation

In [1], Gedenryd maps sequences and networks of the physical and cognitive activities and working materials in design and workmanship, involving the stages of perception, problem understanding, thinking, acting, planning, executing plans, and reflecting upon collected experiences. In this thesis, Gedenryd parallelises thinking and acting with design and production.

In [2], Keller and Keller argue that part of thinking and planning is implemented by the mind using mental simulation that produces mental imagery. This modelling approach is also found in cognitive science as the Perception-Action Cycle [21]. In the domain of design, this notion is found under the term Responsive Design and Fabrication [28]. In [22], the crafting process is described as a “negotiation” between the maker and the material, indicating the uncertainty (or risk) that material individualities pose in the making process. Similarly, in robotic fabrication, the term “negotiated materialisation” has been used [31]. The underlying reality that requires practitioner judgement, dexterity, experience, and tacit knowledge stems from “material uncertainty”, in that quantity, quality and properties of the available cannot be predicted with precision. This uncertainty is dealt by practitioners with through continuous decision-making and motion adaptations.

In [3], crafting processes are semantically modelled to have schemas or plans, and their execution is modelled as individual events. Artefact creation is considered a process that is based on an “archetypa” plan, or a schema. This process schema, is conceptual and ostensive, in that it can be demonstrated and verbally described, i.e., as instructions. The undetermined nature of handcrafting individual craft articles, or “the workmanship of risk” [20], is reflected by process schemas that support branching points to represent practitioner decisions taken during practice, or “on the fly.” The proposed representation analytically associates the segments of these recordings with process steps, to support the abstraction of process schemas from the study of process recordings.

2.2 Simple craft simulators

Craft simulators exist mainly as types of video games or software applications that replicate various aspects of crafting, building, or creating items.

Some games include crafting systems as collections of game mechanics that enable a player to create virtual objects within a game [34]. The central concept in these games (i.e. Minecraft, World of Warcraft) is the “recipe” which, in this context, is defined as follows. A recipe is a representation of the knowledge necessary to transform a collection of game objects (ingredients or raw materials) into a new object[1]. These games do not provide fidelity of action; for example, a tailor in World of Warcraft makes fabric, using nothing but fibre, at the click of a button. On the other hand, they introduce the concept of

[1] For example, a recipe for a pickaxe specifies two twigs and two flint as the materials necessary to create a pickaxe.

affordances, leading a player to perform particular actions within the game world: pickaxes are used for mining, and sewing machines sew fabric.

The Knitting Simulator 2014[2] is a game for the MacOS platform in which the user creates 2D virtual sweaters. The game supports an alternative controller attached to knitting needles. The usage is simple as the needles are used similarly to GUI scrollbars to visualise the progression of the presentation of the sweater image (no 3D tracking of needles or knot simulation is employed). The physical action of moving these knitting needles adds a lot to the otherwise simple game. In addition, they introduce the concept of resource management as the virtual money and time needed to spend within the game to create things.

Woodwork Simulator [23] is a software application designed to recreate the experience of working with wood to build furniture. It provides a range of virtual tools including saws, drills, glue, chisels, and sandpaper to transform blocks of digital wood into virtual user creations. The realism is mainly visual with high-end graphics and operative, in that the user has to “walk” around the workshop to gather tools and materials.

In [8], the “3D Printing Virtual Blacksmith Simulator” is proposed. It is a VR that replicates a blacksmith forge. The simulator allows for the ‘virtual crafting’ of blacksmith objects from horseshoes to coat hooks. It uses VR actuators to monitor the movements of the participant inside the workshop and provides instructions to users on how to create virtual artefacts. The simulator allows for 3D mesh deformation and once an object has been virtually created in the simulator it can be 3D printed allowing for the physical creation of the simulated artefact.

In [25], a method for real-time topological editing of 3D models developed for wood-turning lathe crafting simulation in VR is proposed. The method changes the topology of a 3D model according to the real-world actions of the users which are conveyed to the virtual environment by tracking a VR controller or a VR tracker, attached to a real lathe skew or chisel, and used to simulate the crafting process.

In [5], an interactive diagram model for a simulation training system for traditional craft heritage is proposed. The approach outlines a software architecture for the integration of craft simulation results with the Unity game engine.

Several games exist that simulate pottery wheel-throwing, such as 3D Pottery[3], Pottery Master[4], and Pottery Simulator[5]. Although the graphics are impressive, they do not exhibit a high level of realism.

2.3 Craft presentation systems

The integration of AR and VR into presentations of traditional crafts and education supports the understanding and transmission of craft knowledge. From the superimposition of 3D objects to enhance the spatial presentation of traditional crafts, to the use of VR for educational purposes, these technologies revitalise and provide engaging avenues for education and training. Furthermore, they serve as tools in

[2] https://karastonesite.com/2014/07/19/knitting-simulator-2014/
[3] https://experiments.withgoogle.com/3d-pottery
[4] https://play.google.com/store/apps/details?id=com.create.pottery.paint.by.color&pcampaignid=web_share
[5] https://apps.microsoft.com/detail/XP9K4SFL3CK58X?hl=el-gr&gl=US

the preservation of cultural heritage, allowing for the documentation and demonstration of traditional crafting techniques in a format accessible to future generations.

In [19], a mobile traditional craft presentation system using AR is proposed that superimposes 3D objects of traditional crafts in space. The system enables the operation of 3D objects using a multi-touch surface. Similarly, in [14], VR and handheld controllers are used to interact with 3D models of craft artefacts.

In [13], software simulation tools exploit mathematical concepts embedded in art practices to assist school students in studying mathematics and at the same time learning about beadwork, basketry and other aspects of Native American culture. Evaluation of one of the tools has shown statistically significant improvements in students' mathematics performance as well as an increased interest in Information Technology.

In [27], interactive digital demonstrations through VR for two traditional crafts are provided, relevant to the production of two Greek traditional alcoholic drinks. The approach provided pre-recorded interactions with tools and machines.

In [45], glasswork is exemplified demonstrating the crafting process of a glass carafe is represented visually and semantically in a way that can be utilised in craft training and preservation. The outcomes of the proposed approach were used to implement a Mixed Reality training installation.

In [4], visitors are immersed in a VR environment where they can perform some indicative woodworking tasks relevant to the dovetailing carpentry technique. The simulations are manually modelled pre-recorded and shown as animations, as the purpose of the application is the introduction to the tools of a specific craft.

2.4 Visual simulations

A few works exist that investigate and simulate the appearance of craft artefacts or can be used for this purpose.

In [6], the visual results of painting on fabric are predicted, through a heuristic simulation process. An online simulator for thin-brush dyeing called "yuzen", a Japanese traditional handcraft. The simulator provides a simplified experience, that is, it can be materially unrealistic but mimicking visual appearance. The simulator incorporates various characteristics, including a 2D fluid simulation algorithm that reduces its computational burden. The dyeing algorithm is based on an ink-wash painting algorithm [24].

The 3D Knitting Simulation[6] by the DesignScope Company was developed for flat and circular knitting technology. Given the fabric design, the simulator creates realistic visualisations for Jacquard Raschel, Multibar Lace, and warp-knit fabrics.

In [26], AR is applied to craft-making practices to bring insight into methods of combining virtual and physical materials. The paper recommends that narrative is physically located in craft objects, and while

[6] https://www.designscopecompany.com/simulation-knitting/77/the-art-knitting

virtual elements may describe and annotate an artefact, it is not considered part of the craft artefact's narrative.

Mitsuba 3 [33] is a rendering system consisting of a set of libraries and plugins that implement the graphics rendering functionality of materials and light sources. The system traces high-level simulation code (written in the Python programming language) and simplifies the rendering programming. The system is specialised in differentiable rendering algorithms[7], which makes it suitable for the rendering of dielectric materials, such as transparent and translucent materials (i.e., glass) because it can simulate refraction and reflection phenomena.

2.5 Scientific craft simulations

More realistic simulations of crafts can be found in the field of scientific simulation. In this domain, the state-of-the-art is governed by Finite Element Analysis (FEA) [43, 44]. FEA is a numerical technique that utilises the Finite Element Method (FEM) to simulate and analyse the behaviour of physical systems. FEA is extensively used in mechanical simulation to study and predict the behaviour of mechanical systems under various loading conditions. The basic idea behind the FEA is to divide a complex physical system into smaller, simpler, and very local (or finite) elements. Geometrically, physical bodies are represented by finite elements as volumetric meshes. The behaviour of the system within each element is described by a set of mathematical equations based on the physical laws governing the problem. We adopt this approach for its generality as well as because it is the *de facto* standard in state-of-the-art physical simulation.

Although widely adopted in modern mechanics and engineering, scientific simulation has been not widely applied in the domain of crafts. In [11], the formation of knots is studied using FEM. Mechanical models for fibres are proposed in [12] that account for elongation, bending and torsion forces, and the frictional contacts between them. In [10] the metalworking processing is studied to understand the quenching process and results of a computer simulation based on metallo-thermo-mechanics are presented to know how the temperature, metallic structure and stress/distortion vary in the process.

The situation is much different in the domain of textiles, probably because of their wide application in multiple industries. As such there exists a wide range of software applications for the design of textiles, in other words, visual simulators that illustrate how a woven textile would look like. Prominent examples are WeaveIt[8], Fiberworks PCW[9], ArahWeave[10], pixeLoom[11], WeavePoint, and WIF Visualizer[12]. Moreover, a broad range of studies exist on the mechanical characterisation of textiles (see [35, 36, 37, 38] for reviews). Several pertinent works also focus on how textiles are to deform and distort when worn, e.g. [39, 40, 41]. The most relevant work to the purposes of Craeft is TexGen[13], an open-source software for modelling the geometry of textile structures, as well as including textile mechanics, permeability and

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[7] Differentiable rendering allows the gradients of 3D objects to be calculated and propagated through images, reducing the requirement of 3D data collection and annotation.

[8] http://www.weaveit.com/

[9] http://www.fiberworks-pcw.com/

[10] http://www.arahne.si/

[11] http://www.pixeloom.com/

[12] http://www.weavepoint.com/

[13] https://texgen.sourceforge.io/index.php/Main_Page

composite mechanical behaviour [42]. In the computations pertinent to the manufacturing of textiles, we use the TexGen simulator to model the 3D structure of fabrics.

2.6 Robotic reenactment of crafts

Although that robotic reenactment of crafting techniques is beyond the scope of Craeft, it contains elements of interest to us. The reason is that by being able to re-enact a technique one has to understand its essential elements. The critical point is whether the technique includes judgement so that the computer (robot) has to algorithmically make a decision. By achieving the simulation of practitioners' decisions on the computer we make a step forward in better understanding how practitioners work.

In [7], the carving effect of a range of tools on clay is studied for their robotic reenactment. A series of carving experiments is presented to explore the connection between robotic movement and carved detail, to show the possibility of creating complex forms through robot movement.

In [9], the motion capture of carving tools operated by practitioners is used for the robotic reenactment of stone carving crafts. This research aims to overcome this challenge and bridge the gap between the robotic tool and the real world. In [29, 30], the same approach is adopted to the understanding and robotic reenactment in wood-carving.

3 Simulation elements

In this section, we introduce the elements that govern the representation and simulation of crafting actions. We refer to physics to model the transformation of materials due to the actions of the practitioner.

3.1 Affordances

The concept of affordances stems from psychology and, in that context, it is defined as "what the environment offers the individual" [16]. In the context of crafts, we understand affordances to refer to the tools, materials, and environmental conditions.

Tools are specifically designed to offer these affordances in ergonomic ways. These are affordances that refer to the features of tools about:

1. Their handling and regard the part of the tool that is in contact with the practitioner. For example, hammers have handles that enable a firm grasping hand posture, saws have grips that facilitate pushing and pulling, and loom treadles are flat to be easily stepped on by the practitioner's feet.
2. The action they are used and which are located at the parts of the tool that come in contact with the material. For example, a hammer offers two affordances, through its "face" which is used to strike nails and its "claw" which is used to pull out nails.

The affordances relevant to materials are due to their physical properties which determine the ways it is possible to be treated. For example, wood and marble are suitable for carving and sculpting. The material property of interest is the damage that governs the breaking of wood under mechanical stress. Clay and glass can be moulded and shaped, with the pertinent material property being plasticity. In turn, metals can be forged, soldered, or welded. The elasticity of fibres enables the weaving of fabrics and wicker.

Environmental conditions determine affordances that enable (or not) the possibility of treating materials using tools. Prominent such conditions are temperature, humidity, and ventilation. Temperature and humidity levels are paramount considerations. In woodworking, the propensity of wood to expand or contract in response to shifts in these conditions necessitates a delicate balance to prevent warping or cracking in finished pieces. In pottery, the clay humidity makes possible its shaping. Conversely, heat and ventilation are required to dry paint or fire pottery. In terms of human factors, lighting is an essential factor when precision work is required, such as in silversmithing and sewing. It is characteristic, that before the advent of electricity, weaving workshops were required to have large windows and were mainly located at the corners of buildings to maximise illumination.

In this work, archetypal simulators are used to abstract these affordances so that we can develop them once and then instantiate them for specific materials. In this way, we will not have to develop different simulators for carving different types of wood but only tune the parameters for each wood type. On the other hand, this abstraction has to follow the characteristics of the material due to the damage criteria as, for example, we cannot melt wood or perform glassblowing using cold glass.

3.2 Environmental conditions

Environmental conditions play a significant role in various crafts, influencing the materials used, the crafting process, and the final quality of the product.

In the scope of this deliverable, we examine those that have a direct physical effect on the outcome of the simulated actions, although it ought to be noted that some conditions affect crafting from the human side, such as environment noise, lighting, and safety conditions. (e.g. weather in the outdoors, ventilation in the indoors).

The principal conditions of interest are temperature, humidity, and gravity.

Temperature	Temperature affects the behaviour of materials. Some materials are easier to work with at specific temperatures, while extreme temperatures can impact the curing, drying, or setting processes in crafts like pottery, concrete work, or metalworking.
Humidity	Humidity and wetting levels affect the drying times of materials like paint, glue, or finishes. Moreover, they affect the workability of materials, such as in the case of clay.
Gravity	Gravity plays an important role in techniques that involve viscous materials, such as molten glass. For example, in glass blowing practitioners usually have to continuously rotate the glass body, to counter the effect of gravity.

3.3 Material properties

Material properties are physical, chemical, or mechanical components of a specific material that would determine its functionality and manufacturability. Material properties do not depend on the amount of the material and are metrically measured. A material property may also be a function of one or more independent variables, such as temperature.

3.3.1 Modelling material properties

The material properties of interest **M** differ depending on the action. Material properties can change under different conditions and circumstances. The properties of a material are typically described by physical, mechanical, thermal, electrical, and chemical characteristics. Not all materials exhibit the same sensitivity to these factors, and the extent of property change depends on the specific material and conditions involved. The visual characteristics of surfaces and objects are significantly contingent upon the material composition from which they derive their form and substance. The appearance of surfaces and objects is highly dependent on the material from which they are made.

All material properties are numerically expressed. Each material property is represented as a vector of material property measurements. For many material properties, this vector has a single dimension (scalars), e.g. the density of silver is 10.49 g/cm^3. The expression of other material properties may not be isotropic and require more parameters to be represented. For example, tensile strength, compressive strength, and shear strength are separate parameters used to describe a material's strength under different loading conditions, temporal duration, and spatial vicinity. The principal material properties of interest represented by scalars are the following.

Hardness	Ability to withstand localised permanent deformation and/or resistance to deformation.	Pascal
Density	Mass per unit volume. Determines weight, buoyancy, etc.	kg/m^3
Elastic Modulus	Resistance to non-permanent, or elastic, deformation.	Pascal
Poisson Ratio	Deformation (expansion or contraction) of a material in directions perpendicular to the specific direction of loading.	unitless
Tensile Strength	Amount of load or stress that a material can handle until it stretches and breaks.	Pascal
Yield Strength	Stress corresponds to the yield point (at which the material begins to deform plastically).	Pascal
Hardness	Ability to withstand localised permanent deformation (resistance to deformation).	Pascal
Ductility	Ability to be stretched, pulled, or drawn into a thin wire or thread without breaking.	percentage
Toughness	The ability to absorb energy and deform plastically before fracturing.	$Joules/m^3$
Tensile, compressive, shear strength	Separate parameters are used to describe a material's strength under different loading conditions.	Pascal

Many material properties require multiple parameters for a comprehensive description. Materials exhibit a wide range of behaviours and characteristics, and often, a single parameter is not sufficient to capture the complexity of these properties, that is, for example, elasticity is described by both the Elastic Modulus and the Poisson Ratio. Other multidimensional material properties of direct relevance to crafts are thermal properties, such as Thermal Conductivity or the Coefficient of Thermal Expansion.

There can be multiple models to describe a material property. For example, damage propagation in metals is different in metals and fibred materials and, thus, they require different models; in these cases, two such models are the Johnson-Cook [46] and Hashin [47] models, respectively.

In inhomogeneous material bodies, the expression of material properties is not isotropic. The FE approach is suitable for such a configuration, as individual material properties can be applied per finite element.

3.3.2 Rigidness

The simulation of crafting actions may include unnecessary details that overcomplicate its execution. For example, when using a hammer to cut a piece of wood, we are not interested in simulating the wear of the hammer due to its use. In such cases, we simulate the pertinent objects as being rigid, meaning that their material properties are undefined. In the simulation, objects made from “undefined” materials are treated as imperishable and indestructible.

Rigid objects can be used to model stiff components that are either fixed or undergoing large rigid body motions. The principal advantage is computational efficiency. Element-level calculations are not performed for elements that are part of a rigid body. Some computational effort is only required to update the motion of the nodes of the rigid body.

3.4 Objects

We distinguish objects into two types

1. tools
2. materials and products

The two types of objects do share some properties, which are discussed first.

3.4.1 Object properties

We first note properties common to both object types, namely material properties and pose. We then refer to the treatment of shape in terms of tools and products.

Material properties	Material properties are a time-dependent set of properties of an object; e.g. the hardness of a material is dependent on temperature. Because material properties of interest differ depending on the action the object is involved in, we include them all in every state and classify actions depending on which material properties they affect.
Shape	In general, the shape of both tools and materials may change, and so it is a time-dependent property. Let **S = (V, G)**, where **V** is a list of 3D, floating point locations that represent the nodes of a volumetric mesh and **G** is a list of connectivity indices on these nodes that indicate the hexahedra or tetrahedra of the volumetric mesh. The shape of the object is at an arbitrary coordinate system. As previously discussed, sometimes we model tools as rigid, only to ease the computation for the simulation.
Pose	The pose is a time-dependent property of an object. **P**, (**R**, **T**), where **R** is $[r_x, r_y, r_z]^T$, **T**$[t_x, t_y, t_z]^T$, a rotation, in SO(3), and a translation, in R^3, respectively. Applying them to the coordinates of object O brings it to its "world" pose from the file to the simulated world.

We note that the aforementioned object properties are time-dependent characteristics of objects. That is, the shape and pose of tools and materials change as a result of the crafting actions. Moreover, material properties also change sometimes as a result of these actions, such as when we heat an object to change its shape without breaking it.

Semantically, this change of characteristics over time is represented through the "state" of objects, which changes as a result of actions and/or time; this is described in depth in D2.2. In this deliverable, the simulation results contain this change of state numerically. That is the simulation results discretise time in "frames" (or time instances). In each frame, the new shape and pose of objects are repeated and numerically represented, as described above. The change of material properties is represented in the same fashion, however, in the simulation tools that we use, we have to explicitly request for its computation.

3.4.2 Tool Properties

The shape of tools in crafts often plays a crucial role in determining their affordances, influencing how they can be used for specific tasks. Following [15], we classify tools according to their purpose to cut, pinch, grip, drive, strike, apply, and constrain materials and bodies. Tools are conventionally non-powered in traditional crafts and, so, we emphasise first such. However, there are no implications for this study as to whether they are electrically or manually powered.

Assuming tool rigidness simplifies computation because the simulation does not compute tool deformation. When the geometry of a tool changes, it follows (prescribed) mechanical constraints which ease its modelling and simulation; individually, each tool part is considered rigid. Changes in tool shape are often disregarded in the simulation of individual actions as they are minute and regard the long-term wear of tools. In contrast, products are typically considered as deformable.

3.4.3 Material and product properties

Products are processed raw materials at any (final or intermediate) processing step. Thus, we classify materials and products under the same type, because:

The product of one craft may material of another, e.g. thread making provides material to fabric making, which provides material to textile making, which provides materials to garment making.

The outcome of a process step is an intermediate product that is the input “material” to a succeeding process step.

Materials and products change state at and due to the occurrence of events. Following the state-based approach of the Mingei ontology, an object is an endurant that has time-independent and time-dependent properties.

The object is modelled as a symbol to which we attach: (a) the never-changing time-independent properties, such as its material composition, and (b) a series of states, each consisting of a value for the time-dependent properties. Then, every time some time-dependent property of the object changes, we create a new state of the object with the new values. This new state becomes the current state of the object’s time-dependent properties. The states the object goes through during its lifetime form an ordered chain in time, and actions play a causal role in determining the passage from one state to the next. The time-independent part of an object includes invariant descriptive properties and shape, while the state of an object includes pose and all material properties that may be affected by an action.

3.5 Causing entities

We call causing entities the reasons (or phenomena) that bring changes in the state of objects and materials in the scene. In the crafting context, these are force and motion. The expression of these entities occurs in time. Furthermore, sometimes the “null” action, namely waiting, is also purposeful and useful.

3.5.1 Force

Force is central to crafting actions, serving diverse purposes throughout the process. Practitioners employ force to shape and form materials, cut and separate components, join materials together, and control tools with precision. It plays a key role in material deformation, removal, and energy transfer, influencing the rate of material removal and the quality of surface finishes. Forces are also important for maintaining stability and balance during crafting, and they contribute to structural integrity and the assembly of crafted objects. Forces are classified into direct and rotational forces (torque).

The application of a force is an event, which occurs in time and space. The application of force has a temporal duration. Sometimes, it is practical to assume that this duration is infinitesimal.

The force itself is a quale of the object, that is a value (in a value space) that a certain characteristic of an object (i.e., an action) can assume. That is, the same way we analyse "the colour of the rose is red", as "the rose" is the object, "the colour of" is a quality and "red" is a quale, we analyse "the hammer hit the nail with force F", as "the hitting" is the object (perdurant), "the force of" is a quality and F is a quale, i.e., a value of the force. In the Conceptual Reference Model (CRM), we say that "the force of" is a (measurable) property of an action and F is a dimension, that is a value that the property can take.

To model force we use **F**, [**v**, t, **a**], where:

- **v** is $[v_x, v_y, x_z]^T$, in R^3, is the direction of the force in Cartesian coordinates; **|v|** is the magnitude of the force.
- t is the force duration, which can be a single instant or a time interval, and
- **a** is the force spatial profile which describes how the force is applied upon an object or material. This can be a single point, a surface area, the entirety of a material body (e.g. gravity), and others. Depending on the profile, the data describing it will vary in dimensionality.

Force is a time-dependent entity because throughout a time interval **v** and **a** may change. To digitise this variability, we discretise the time interval at a *sampling rate* and represent the values of **v** and **a** at several states that match this rate. In the computer, the values of **v** and **a** are stored in matrices.

It is recalled that gravity is a constant force applied to materials and that it has a central role in crafts that deal with viscous materials (e.g. glassblowing) as well as crafts that relate to the building of structures (e.g. masonry).

3.5.2 Motion

Another option for describing events is through the motion of scene elements. This is important when data is collected from visual observation, where forces cannot be directly measured. In several cases, it is convenient to describe practitioner action through motion as force can be variable over time and dependent on material individualities, as well as on the individual weight of tools and quantity of material.

Crafts often involve intricate hand movements and manipulation of materials. Many crafts require fine motor skills for precision and control, which can be very specific according to the crafting task. For example, in carpentry, the use of saws and in pottery the use of a wheel is more intuitively described through motion rather than the forces required to produce this motion.

Furthermore, in several cases, coordination and synchronisation are more conveniently described through the motion description, albeit forces are also temporally represented. This is the case, for example, in glassblowing, coordinated motion is often required by two persons (master and assistant) and in pottery a synchronisation of foot pedal control and hand movements is required.

Motion is conventionally described as a change of pose and is defined with six (6) parameters **V**, [**T**, **R**, t], where: **R** is $[r_x, r_y, r_z]^T$, **T**$[t_x, t_y, t_z]^T$, a rotation, in SO(3), and a translation, in R^T, respectively, and t is the motion duration time interval.

3.5.3 Waiting

Waiting plays a significant and often overlooked role in crafts. In many crafting processes, waiting is a necessary and intentional step. Waiting is essential for allowing materials to cure, dry, or set in activities like pottery, painting, and woodworking. During this waiting period, adhesives and finishes bond securely, and chemical reactions, such as oxidation in metalworking, contribute to the final appearance of crafted items. Moreover, waiting is related to the control of thermal and wetting conditions of materials and objects (cooling, heating, wetting, drying). Ageing and resting periods are intentionally incorporated into certain crafts like brewing or winemaking, enhancing flavours and textures. Waiting is also a key element in quality control, allowing craftsmen to assess results before proceeding, and it is influenced by environmental factors like temperature and humidity.

Waiting is represented by a positive scalar, t.

3.6 Constraints and conditions

Constraints refer to the restrictions or limitations applied to the model to simulate realistic conditions. These limitations can include physical restrictions or geometric constraints that the structure or system must adhere to during analysis.

An example of such a restriction is the workbench of a practitioner that holds materials in place during practice. Another example is a vice that holds a specific piece of material in place while the practitioner works on it.

Constraints are used to define the mechanical context of the simulation. In the previous examples, we are assuming the workbench shape and location as constant. Of course, the workbench may get dislocated by a severe force of the practitioner. If we would like to simulate this possibility, we would have to add the workbench as a simulated body and use the ground plane as a constraint. Similar is the case for the vice, which is considered as constant and we do not have to simulate the workbench that is mounted on.

In other words, constraints define the geometrical and mechanical context of the physical system under consideration.

3.7 Actions

We classify and abstract actions into four basic categories. The reason for doing so is to study them separately and identify the material properties, behaviours, and affordances relevant to each action type. In this way, we aim to facilitate and simplify the realisation of both archetype and craft-specific simulators.

3.7.1 Subtraction

Damage refers to material degradation or failure. In FEM analysis it is relevant in cases where materials undergo progressive deterioration or failure under load. This corresponds to the gradual reduction in material properties, such as stiffness or strength, under load. Depending on the material, the result may be cracking, yielding, or plastic deformation. Damage models are often coupled with constitutive models that describe the material behaviour under various loading conditions.

To initiate the simulation of damage a critical condition must be met. This is assessed by failure criteria that are based on the evolution of damage variables, and simulation results can be analysed to identify regions where failure is likely to occur.

Various damage models exist, each tailored to specific material behaviours and failure modes. Examples include cohesive zone models for simulating crack propagation, damage plasticity models for metals, and continuum damage mechanics for composite materials.

In the context of traditional crafts, we have selected the following, given the materials we are dealing with:

- The Orthotropic Damage Model (ODM), is suitable for wood, as wood exhibits different material properties along different directions, due to its fibrous structure. This ODM enables the simulation of damage evolution in each material direction independently.
- The Cohesive Zone Model (CZM) is used for simulating crack initiation, propagation, and cohesive failure in brittle materials, such as marble and glass.
- The Johnson-Cook model is widely for simulating ductile material behaviour, particularly in metal forming processes. It accounts for isotropic and kinematic hardening and includes parameters to capture the effects of strain rate and temperature.
- The Damage Plasticity model combines plasticity and damage mechanics to simulate the behaviour of materials undergoing both plastic deformation and damage accumulation, such as clay.
- The yarn-level model focuses on modelling the fabric at the yarn level, considering individual yarns as distinct entities. As such, strain-based damage models are more suitable for fabric rupture, where failure is determined by reaching a critical level of strain. It is, furthermore, noted that woven fabrics rupture based on the type of the weave.

The material properties of relevance to damage are the following:

- Strength is modelled by tensile strength, compressive strength, and shear strength, which determine the resistance of materials to cutting forces and the likelihood of fracture.
- Fracture Toughness measures resistance to crack propagation and is relevant when modelling crack initiation and propagation during cutting.
- Hardness models the ease with which it can be cut.
- Thermal conductivity and heat capacity, model the generation of heat during cutting processes and the likelihood of material melting due to the generated heat.

3.7.2 Shaping

Material properties are relevant to the shaping and deformation of models, and how materials can be worked, formed, and manipulated. Intuitively they are the properties required to perform “freeform” transformations, that is a change of shape that preserves its mass.

- Malleability models the ability of a material to be deformed and shaped without breaking or cracking.
- Ductility models the ability of a material to be stretched or drawn into a wire or thin sheets without fracturing; it is a common property for all metals except for Mercury.
- Hardness measures the resistance to deformation or scratching.
- Elasticity measures the ability of a material to return to its original shape after being deformed.
- Brittleness is the tendency of a material to fracture or break when subjected to stress; intuitively it is associated with fragility.
- Plasticity models the ability of a material to undergo permanent deformation without breaking and is essential in moulding methods.

3.7.3 Adding

Additive craft actions involve building or creating objects by adding material. The relevant material properties are as follows.

- Adhesive properties relate to the ability of materials to bond or adhere to one another. They are relevant to adhesives such as glue and mortar.
- Viscosity and flowability are relevant to the application of adhesives.
- Curing and setting time regarding the time required for adhesive to change state from liquid to solid. Typically, during this time the built structure has to stay stable.

3.7.4 Interlocking

Interlocking actions are used in the assembly of structures that rely on the secure connection of individual components. Interlocking actions manifest differently depending on the physical properties of the materials. For example, friction and flexibility are central in textile manufacturing as they hold fibres together. In contrast, in woodworking the hardness of a nail is essential

- Friction material properties determine whether the interlocked components will “hold together”, or otherwise if the assembly will be stable.
- Hardness determines whether the materials will interlock or break due to the exercised tension.
- Plasticity determines whether the interlocked materials will flex, bend, break, or retain their shape during their assembly.

3.8 Implementation

For formalising and executing the simulations the Simulia Abaqus FEM solver was employed. The executions were parallelised on the available cores of the computer. Finite elements were modelled using hexahedra of 1 mm3. The typical execution time for the modelled simulations was in the range of 30 minutes to 2 hours, on 4 CPU cores.

The output was stored in two forms.

1. Volumetric, in STEP format that encodes the volume representation of objects and materials, in hexahedra.
2. Surface, in OBJ, PLY, and WRL formats encodes surface meshes of triangles.

The volumetric output is useful for reusing the output of the executed simulation in new simulations. This is important when the judgement of the practitioner needs to be simulated or assessed. The reason is that FEM simulators do not deal with algorithmic decisions that pertain to prior knowledge and experience. As such, the simulation outcome needs to be evaluated by other pieces of software which will determine if a new simulation is required. A simple example of such a case is the following. Suppose that a practitioner is striking a piece of wood with a hammer and the goal of cutting it into two pieces. Depending on the force of the practitioner, as well as the thickness and density of the wood a different number of strokes is required. The simulator can predict the outcome of individual strokes but does not know the goal of the person. If we are to simulate the judgement of the practitioner, we need another piece of software that would evaluate if the piece of wood was cut or fractured, after each stroke. If the piece of wood has not been cut, then the volumetric representation is required as input for the next simulation step.

The surface output is useful for integrating the simulation results with the 3D software (Unity) that will create immersive experiences. The reason is that, in this case, the volumetric composition is not required and only the surface suffices for the graphical rendering of objects and animations (see also Section 6).

4 Action modelling

In this section, we define the entity and action types which we deal with, in the context of manufacturing in general, and traditional crafts in particular. In Section 4.1, the ontology of entities is aligned with the maker-material negotiation model that is introduced and elaborated in D1.2. It is here briefly presented to correspond this model with the simulation taxonomy presented in this deliverable. In Section 4.2, actions are taxonomised and treated as functions on the state of the scene and its elements. This taxonomy is then corresponded with the types of simulations implemented in Section 5. Last. in Section 4.3, a methodological tool is presented, the action description template, which facilitates the encoding of actions from conceptual to simulation level.

4.1 Ontology

We review the ontology to describe the entities that are relevant to actions and virtual actions, as well as their schemas. We model actions and action schemas in the same way as we do for processes and process schemas (see Section 2).

4.1.1 Actions

Actions are modelled in a very similar way to processes (see Section 2).

- Actions are events that occur when action schemas are executed.
- Actions are associated with intentions.
- Actions are elementary, in that they cannot be further analysed.

Due to the last property above:

- A process step may be analysed into an arbitrarily deep hierarchy of steps and sub-steps.
- A process step includes at least one action.

4.1.2 Action schemas

Action schemas are modelled in a very similar way to process schemas (see Section 2). Intuitively, action schemas and process schemas are plans. The process and action schemas are the ideals. They come from abstraction that can only be through wisdom (high experience).

The intention of an action is associated with a plan, which is called action schema. The anticipation of the result of this plan is the anticipated state of the workspace scene after the occurrence of the action. This state is called simulated mental imagery [2]. In the computer, we encode this state as usual (that is as any other step).

4.1.3 Transitions

Action schemas are linked into step or process schemas using the same five types of transitions, as we do for process steps in [3]. That is:

Transition	unconditional passage from one step to the next
Fork	connects an action schema with subsequent action schemas performed in parallel
Merge	where two or more action schemas unite.
Join	connects a schema step with the schema step that should be completed before any transition and with the next step to be performed.
Branch	a decision step that accepts one incoming edge and selects one outgoing alternative. Branch nodes control the flow of a process by selecting one of several alternatives, based on the outcome of a condition evaluation.

4.1.4 Causing entities

Causing entities model the physical powers that drive the occurrence of actions. In ontology terms, they are the models of the physical mechanism that describes action causality. Typically, causing entities are the "driving forces" that put "actions in motion" and provide the power and energy for the execution of an action.

We have two ways of modelling action causality. The first is by modelling the forces that drive tools during material transformation as well as auxiliary forces that are often required, such as stabilisation forces[14]. The second is by modelling their object motion. In recordings, the second way is more accessible because tool motion is relatively simpler to measure than the force exercised by a practitioner.

4.1.5 Transformed entities

Transformed entities are those whose state after the action is different from before the action. They refer mainly to the tools used in the action. It ought to be noted that the state changes for the transformed materials as well, but these entities are treated differently because they become part of a new entity, so their new state is recorded with the state of the new entity.

4.1.6 Created entities

Created entities are those whose existence is considered to start from the completion of the action and as its result. In the initial steps, created entities such as a gathering of liquid glass, a quantity of clay, or a piece of wood. Created entities are also considered those which are the result of the modification of a previous entity, during processing. In addition, create entities can be composite objects, which are created after the joining of two entities. Not all of the created entities are of direct interest, such as a chip of wood carved out during the creation of a wood sculpture.

4.1.7 Ceased entities

[14] When hammering a nail in a piece of wood, the driving force is exercised on the nail by the hammer. The two finger that hold the name in place are called stabilisation forces.

Ceased entities are those which cease to exist after and as a result of the action because they are combined into a new entity. An example is a nail that is driven into a piece of wood that will eventually become a piece of furniture.

4.1.8 Virtual actions

Virtual actions are simulated actions that occur in a virtual world. They are “observable” through the simulation results which are stored in the file. The contents of this file are machine-interpretable and can be visualised.

It is noted that although earlier in this document we are discussing new, modified, and ceased entities, this characterisation is not provided by the FEM simulation engine. For this information to be obtained the simulation outcomes have to be analysed.

4.1.9 Virtual action schemas

Virtual action schemas are the simulation plans. The virtual action schema is a set of human-comprehensible instructions on the simulation functions that should invoked and their parameters. This instruction regards the identification of the mechanical laws and models that should be used, along with simulation parameters such as the geometry of the involved bodies, their poses, their material composition etc. The virtual action schema is eventually transcribed into a simulation input file (see Section 5). The FEM engine reads this file and performs the simulation according to the instructions found in this file.

4.2 Action types

In crafts, actions transform materials. Action is “the unit activity attended by a practitioner” [2]. Action plans are hypotheses for the achievement of goals, under prescribed conditions on the state and the spatial arrangement of materials.

We distinguish between transformative and auxiliary actions. Transformative actions change the shape of materials and are further classified into Add, Subtract, Interlock, or Plastic transformations, as explained below. Auxiliary actions are ones at which a practitioner changes the placement of an object, moves a tool to the appropriate place to perform some action, or waits.

The aforementioned distinguishment is only conceptual and not technical. That is, although we distinguish between the two in conceptualisation we do not do so technically. Moving and waiting are modelled in the same fashion. Specifically, moving an object is a change of state that affects solely its pose. Waiting is considered a “null” change of state. These actions are defined below.

4.2.1 Additive

Additive actions refer to events where materials are built up or combined to create a final or intermediate product. These actions involve constructively adding or layering materials. In additive actions, the crafting process involves a step-by-step accumulation of materials, resulting in a final product that reflects the deliberate addition of elements. Examples are the addition of tiles to create a mosaic, joining pieces of metal together in metalsmithing, building with bricks and mortar, or adding a layer of glaze on a ceramic pot.

object = Add(object or zero)

Additive actions involve building materials to achieve the desired form, contributing to the accumulation of material. Often adhesive materials (e.g. glue, cement) are used in additive actions.

4.2.2 Subtractive

Subtractive actions involve the removal or carving away of material to achieve the desired form or design. Practitioners take away material to reveal the final product. Subtractive actions require precision and skill, in removing material to reach the intended form. Examples are wood and stone carving, or metal engraving.

object, objects or zero = Subtract(object)

4.2.3 Plastic

Plastic, from Greek *πλαστικός*, pertains to the ability of a material to be moulded, shaped, or manipulated. The plastic transformation follows the principle of mass preservation. Plastic actions involve the malleability and formability of materials to achieve the intended shape or structure. Plastic actions are characterised by the capacity of materials to undergo deformation without breaking, allowing practitioners to manipulate and shape them into intricate and detailed forms. Examples are the shaping of clay in pottery, bending plies to make boats, and shaping hot glass and metal in blacksmithing and glassblowing, respectively.

object = Plastic(object)

4.2.4 Interlock

Interlocking actions refer to events where components are designed or manipulated to fit together seamlessly, creating a unified whole. This can involve the use of interlocking joints, knots, or the assembly of elements that fit together like puzzle pieces. Some examples are the weaving of threads in textile manufacturing, interlocking metal rings in chain making, interlocking joints, nails, and screws in woodworking, and weaving of wicker in basketry.

object = Subtract(object, object)

Interlocking and additive actions differ interlocking actions involve connecting separate components to form a cohesive whole, while additive actions entail building up material to create a final product. Interlocking actions involve connecting or fitting separate components together typically resulting in a cohesive whole where individual elements are securely joined.

4.2.5 Move

Moving objects is often required to put materials in place or to position tools at the preferred location for their use. An example is the positioning of a piece of wood on a workbench, the positioning of a nail at the appropriate place on this piece, and the placement of a hammer at the correct position to drive this nail into the piece of wood.

object = Move(object)

4.2.6 Wait

Waiting is often used in crafts when the practitioner waits for a heating, cooling, wetting, or drying action to be completed.

Wait(time)

4.3 Action description templates

Action description templates are used to describe the actions to be modelled. These templates reflect the attributes of entities in the ontology and serve as a first means of collecting input. They are used to formalise the collection of information for an action. Action description templates specify the name of the action, the participating entities (causing, transforming, absorbed, created) and the type of simple machine or machines involved. When an action template is completed, the input of information in the MOP/CAP is facilitated. An action description template is shown in the inset below.

English name for the action type (a piece of text, e.g., "inserting a chisel into a piece of wood").

Optional textual description of the action type for the human (a piece of text, e.g., "the action is performed by a single agent that hits the chisel by a hammer to the end of inserting it into a piece of wood. It belongs to the X craft etc,")

Function of the action type according to the standardised vocabulary (a URI)

Type (one of *Add, Subtract, Interlock, Transform*, encoded as a URI or as a character string)

Machine Type (one or more of the six Archimedean simple machines or a physical or chemical agent, encoded as a URI or as a character string)

For each causing entity:

- **Type** (e.g., "force for hitting the chisel")
- **documentation** (e.g., "the force is described by giving its intensity, velocity and direction, all in a single file")

For each transformed entity:

- **Type** (e.g., “hammer hitting the chisel”)
- **Documentation of the unchanging properties** (e.g., “a hammer is described by giving its length, weight and material, all in a single file”)
- **Documentation of the state of the entity before the action** (e.g., the shape of the hammer given as a mesh in a separate file, the pose of the hammer given as 3 coordinates in a separate file)
- **Documentation of the state of the entity after the action** (e.g., the shape of the hammer given as a mesh in a separate file, the pose of the hammer given as 3 coordinates in a separate file)

For each absorbed entity:

- **Type** (e.g., “chisel inserted into the piece of wood”)
- **Documentation of the unchanging properties** (e.g., “a chisel is described by giving its type, length, depth, height, weight and material, all in a single file”)
- **Documentation of the state of the entity before the action** (e.g., “shape of the chisel given as a mesh in a separate file, position of the chisel on top of the piece of wood given in a separate file”)
- **Documentation of the state of the entity after the action** (e.g., “shape of the chisel given as a mesh in a separate file, position of the chisel inside the piece of wood given in a separate file”)

For each created entity:

- **Type** (e.g., “piece of wood with chisel inserted into it”)
- **Composition** (e.g., “two parts: chisel and piece of wood”)
- **Documentation of the state of the entity after the action** (e.g., “shape of the composite object given as a mesh in a separate file”)

5 Simulations

Action simulations are predictions of the execution of real actions. These predictions regard the evolution of the state of physical components in simulated scenes during the simulated time interval that virtual actions last. These predictions are produced by functional mechanical models in software that when executed ("run") generate them.

We provide an orientation to the computational mechanisms that are employed to implement these simulations. Then we provide a categorisation of actions based on the type of transformation they induce. Finally, we present implementations of these archetypes in the computer.

5.1 Orientation

In this orientation subsection, we introduce our approach towards creating generative mechanical models in software, using FEs.

5.1.1 Finite Elements

FEM simulators encompass the models and equations of the mechanics that govern the interaction of matter at a very local level. The equations predict the state of the matter at that very local level (per finite element) and in the very brief future. The inputs to these equations include material properties, forces, velocities, and environmental conditions. There exist several models, and corresponding equations, for different types of materials (e.g. metals, crystals, fibrous materials, bubbles) and the physical states (i.e., solid, liquid, gas) that they are in. By iterating, predictions can regard longer time intervals.

The simulator takes as input the virtual simulation schema, which contains the plan of the events to occur in the simulation. The execution of the simulation plan in the computer, or simply a simulation, considers a representation of the scene elements and the planned action upon them and outputs a representation of their state during and after the action.

FEM simulators are generic, in that they provide equations for all types of physical phenomena. It is, thus, important that the mechanical mechanisms that govern each action are correctly modelled. In the following, archetypal simulation models are presented.

5.1.2 Rationale

In the mechanical context, the following types of events can be simulated.

- Force/Velocity-oriented, where the forces of initial velocities that will govern the simulated event are provided as input. The simulator predicts the final pose and state of the objects.
- Motion-oriented, where the displacement of some scene elements is defined. The final pose of objects is pre-determined.
- Hybrid, where these definitions are combined.

5.1.2.1 Motion-oriented simulations

Using video or MoCap, we can measure the motion of dynamic elements in a real scene, without measuring the forces that were needed to realise these movements. This is useful because:

1. Measuring motion from video or MoCap is simpler than force measurement[15].
2. When some forces are not of direct interest, such as those of non-hand-powered tools; e.g., we are not interested in the force that rotates a lathe, so, we model this motion as a given. Instead, we are interested in the forces that a woodturner uses to move a chisel in the turning wood (see below).

5.1.2.2 Force-oriented simulations

The prediction of the outcome of forces and initial velocities are problems that are widely studied in mechanics. This is useful in:

1. Predicting the stability or behaviour of objects before implementing them.
2. Producing realistic interactive environments of virtual actions and, in particular, the force that needs to be exercised by the practitioner.
3. Predicting the brittleness of artefacts before their manufacturing.

5.1.2.3 Hybrid simulations

It is possible to combine both simulation types. The woodturning example with a lathe is characteristic. We are not interested in the mechanics of an electrically powered lather and, thus, model it as an unobstructed and uninterrupted motion. The mechanics of the chisel being pushed in the turning wood are more interesting to be modelled with forces because we can assess the force needed by a person to perform woodturning with some particular type of wood.

5.1.3 Simulation input file

The contents of a completed action template comprise a human-comprehensible description of a virtual action schema (see Section 4).

This description simplifies the transcription of these contents into a simulation file, which is the machine-interpretable file with the instructions for the simulator.

This transcription can take place in two ways:

1. Using a GUI, which provides design tools, data input facilities, and access to the mechanical models available. A human user reads the template and selects the appropriate materials, models and parameters, to faithfully represent the scene and actions described in the plan.
2. Using a computer program that generates this file, by instantiating existing action archetypes, to which the contents of this file comply. If the virtual action schema can be matched to an

[15] Measuring mechanical forces requires specialised, pervasive, and tedious sensor configurations for the recording.

archetype, then the mechanical principles can be copied from the archetypes and specialised ("instantiated") for the parameters of the particular virtual action.

Although the simulation file is to be accessed by the computer, we opt to be in text format and human-comprehensible. This eases the debugging, at least for this early stage of our work.

The input simulation file represents the entire plan of the simulation, the forces, velocities and constraints involved, as well as the shape and material properties of the entities involved. The measurement units of all physical quantities in the simulation file are in the SI system. The entities defined in the simulation input file are presented in the table below.

Bodies	A list of the objects in the simulation as separate parts. For each part, its 3D geometry and composition are represented. The geometry of each part is represented in its arbitrary coordinate system. A material is assigned to each part.
Material	This part contains a list of the materials used in the simulation. For each material a label is provided and a list of material properties. Each material property is represented as a vector of material property measurements. For many material properties, this vector has a single dimension, e.g. the density of silver is 10.49 g/cm^3. Other material properties are not isotropic and require more parameters to be represented. For example, tensile strength, compressive strength, and shear strength are separate parameters used to describe a material's strength under different loading conditions.
Assembly	Contains information related to the assembly of finite element models. This section defines how different components or parts come together in the simulated scene, containing the pose transformations to bring elements into the common coordinate system.
Loads	Contains information about the dynamic events that will be simulated, such as the forces, velocities, displacements and rotations to be simulated, as well as the environmental conditions (and possibly their change) during the simulated time interval.
Scenario	Contains information on the timing and duration at which forces are exercised, movements take place, and environmental conditions vary. This information is stored in temporal order.

We use two formats for simulation input files, the CAE and INP formats. The first is a binary format used by the Simulia Abaqus suite. The second is a text-based, human-comprehensible format that is compatible with said suite. We opt for the latter format because it is simpler to parse and modify, either by the programmer or the software that we write. In this way, we can dynamically produce INP files by software and link independent simulations. This is important when we wish to involve "judgement" on the result of a simulation and dynamically generate an INP file with the actions dictated by the action or process schema given the outcome of said judgement.

To enable the reproducibility of the archetypes in this deliverable, the INP files for the archetypes presented below are provided as an attachment to this deliverable, online in the Zenodo platform [48]. Moreover, this dataset contains video animations of the archetypal simulators presented in this section.

5.1.4 Simulation output file

The output file contains the state of the parts during and at the end of the simulated time interval. This file contains a wide range of information related to the simulation results. This information includes nodal and elemental displacements, stresses, strains, reaction forces, etc. These outputs can be visualised through plots, animations, and reports.

The output file does not contain semantic information as to whether these parts are in one piece, if the outcome is correct, etc. This information has to be computed by accessing the output file. Using the output file, the simulation can be visualised and measurements of the resultant structures and dynamics are enabled.

5.1.5 Visualisation of simulation results

In the next subsection, the results of simulation archetypes are presented. In all cases, their visualisation follows the following conventions. Three frames are presented for each archetype: the first, the middle, and the last. All frames show the scene from the same viewpoint using a perspective virtual camera. The finite elements of the simulated bodies are shown as meshes of opaque hexahedra and, in some cases, as meshes of tetrahedra (depending on the modelling followed). The colour of the visualised represents the mechanical stress occurring at each element, as a result of the simulated events.

5.2 Simulation archetypes

The action archetypes are analysed to create a simulation archetype which can then be refined into a specific simulation for each craft action of interest.

The presented taxonomy of simulations is aligned with that of the maker-material negotiation model in D1.2. Furthermore, the simulated action archetypes are semantically annotated using the Getty Arts and Architecture Thesaurus, by providing a link to the term that each action corresponds to. This annotation is hierarchical and aligned with the maker-material negotiation model. That is subtractive actions are subclasses of the "subtractive processes and techniques", additive actions are subclasses of "additive and joining processes and techniques", etc.

For each simulation archetype, the filename of the simulation input file is also provided. In the examples that investigate multiple conditions, multiple simulation input files are provided one for each condition.

5.2.1 Subtract

http://vocab.getty.edu/page/aat/300229471 - <subtractive processes and techniques>

Actions that remove material or split materials in parts are classified as subtractive actions. The action returns at least two parts. In the simulation of subtractive actions, material properties that describe the damage and fracture of materials under stress are important.

Of central importance in subtractive actions is the damage model and its evolution, which defines the way that the material becomes separated into two or more parts. Moreover, the shape of the tool determines the way that material is subtracted.

5.2.1.1 Cutting

http://vocab.getty.edu/page/aat/300053069 cutting (shaping or dividing)

Simulation input file: 01_cutting/y643.inp

The majority of cutting actions take place with the use of a sharp tool that implements the wedge simple machine. The archetypal simulation of cutting is implemented by a wedge. Depending on the material type and the velocity of the tool, smaller fragments of the material may be produced.

In the simulation shown in Figure 1. Simulation of a wedge cutting a piece of material in two pieces., a rigid wedge moves downwards and cuts a piece of material.

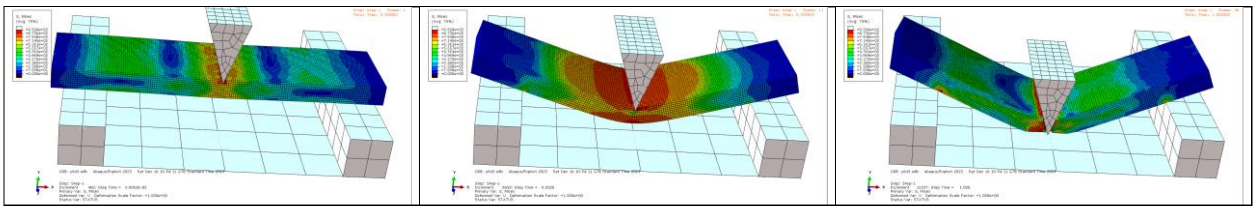


Figure 1. Simulation of a wedge cutting a piece of material in two pieces.

The example is made generic by the addition of the two supporting structures. This allows the material to be distorted, according to its plasticity parameters. The distortion is analogous to the height of these structures, while for zero height, zero distortion is obtained. Variants of this archetype can be obtained if the contact angle of the tool with the material is modulated. Moreover, other variants can be obtained if the supporting structures do not share the same height.

In the archetype, it can be observed that the mechanical tension is increased (middle frame) until the damage condition is met and the piece of material breaks. The ground place is utilised for realism, in that it constrains the motion of the cut pieces.

5.2.1 Carving

http://vocab.getty.edu/page/aat/300053149 - carving

Simulation input file: 02_carving/jnew.inp

Carving and engraving are very similar to cutting and, therefore, we do not repeat all the information from the previous case. The underlying mechanism is also the wedge. However, there are some significant differences, which are studied below.

The first is that the archetype is modelled based on the trajectory of the carving tool. This is because the interest is in simulating the gesture of the practitioner. Moreover, the trajectory determines the shape of the carved material. The second is the stabilisation force that has to be applied to the material so that it remains stable in place and is not pushed away by the carving tool.

In the simulation shown in Figure 2. Simulation of a carving action., a rigid chisel moves across a piece of material, carving a part of it. A straight line is set as the trajectory.

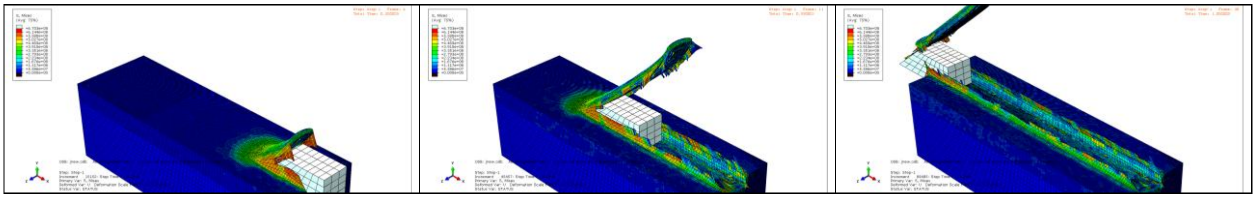


Figure 2. Simulation of a carving action.

The next carving example demonstrated the potential of integration of the tool trajectory with recordings of practitioners, obtained either from object (tool) tracking or MoCap. In the example, the tool moves in a sinusoidal trajectory on the surface of the material. This trajectory has been numerically defined and inputted to the simulator in the form of 6D coordinates (3 coordinates for this location and 3 coordinates for its orientation in space).

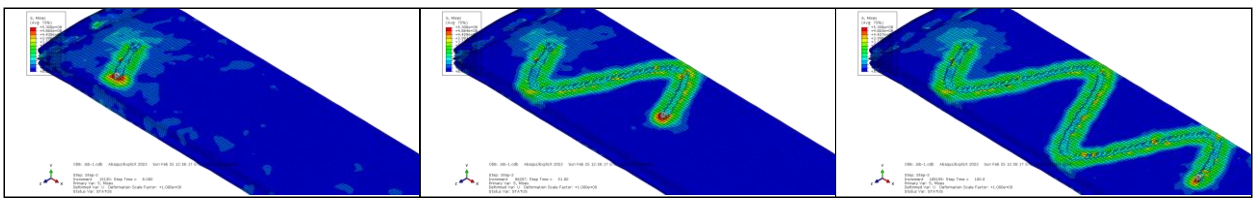


Figure 3. Simulation of a carving action with a numerically defined trajectory.

5.2.1.3 Turning

http://vocab.getty.edu/page/aat/300053158 - turning (shaping process)

Simulation input file: 03_turning/xaxis.inp

A lathe is a machine tool that rotates a workpiece about an axis of rotation to perform various operations such as cutting, sanding, knurling, drilling, deformation, facing, and turning, with tools that are applied to the workpiece to create an object with symmetry about that axis. In traditional crafts, the lathe was powered by the practitioner, typically using his/her feet and a pedal. Nowadays, lathes are electrically powered.

Turning is very similar to carving, in that a wedge-based tool is used to subtract material. The lathe provides stabilisation so that the tool can be pushed against the rotating material. The underlying mechanism that rotates the material is based on the wheel and axle simple machine. The carving mechanism is based on the wedge simple machine.

In Figure 4. Simulation of a turning subtractive action., the archetypal simulation for turning is shown.

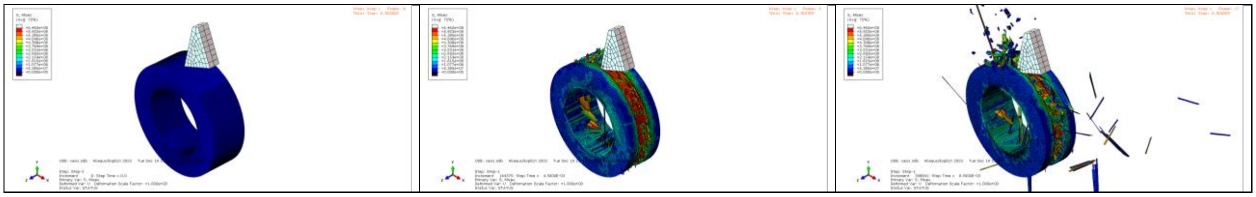


Figure 4. Simulation of a turning subtractive action.

5.2.1.4 Dismantling

http://vocab.getty.edu/page/aat/300061163 - dismantling

http://vocab.getty.edu/page/aat/300053748 - separating

Simulation input files: 04_dismantling/Job-1.inp, 04_dismantling/Job-2.inp

Dismantling or separating parts by pulling them apart is a subtractive process. The underlying principle is a couple of forces in (approximately) opposite directions that increase mechanical stress until the damage condition is met at some part of the material.

In Figure 5. Simulation of splitting a material part into two pieces by pulling it apart., shown is the archetype of dismantling a piece of material for two conditions. In the first (top), by pulling it apart from its two sides, the practitioner uses two forces to pull the material apart from its two opposite edges. In the second, a rotational component is added, as if the practitioner would rotate his/her right-hand wrist while pulling apart. The way that these forces are exercised determines the location where the material fails (breaks).

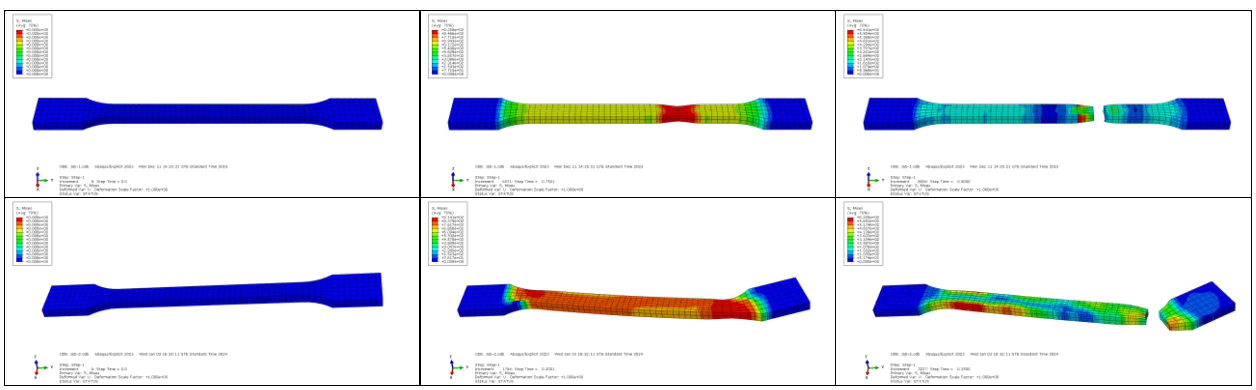


Figure 5. Simulation of splitting a material part into two pieces by pulling it apart.

5.2.1.5 Compressing

http://vocab.getty.edu/page/aat/300220420 - compression

Simulation input file: 05_compressing/Job-1.inp

Compression is the opposite of dismantling. It regards pushing a material to reduce its size. Depending on the stiffness of the material it may only distort, but after a point of failure, it starts breaking apart losing part of its mass as it breaks apart.

The archetypal simulation below demonstrates such a case for a stiff material bar that is compressed from its top.

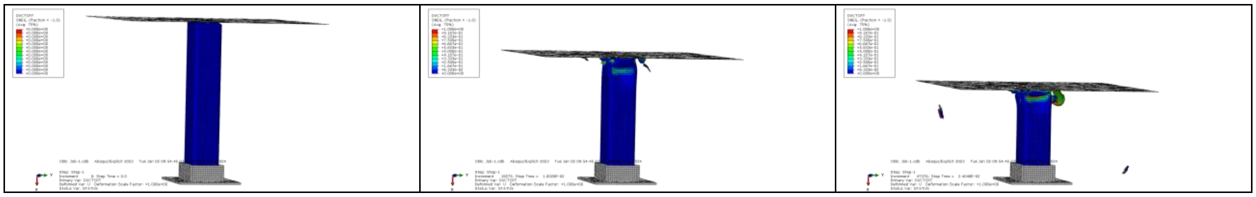


Figure 6. Simulation of material compression

5.2.1.6 Drilling

http://vocab.getty.edu/page/aat/300053151 drilling (process)

Simulation input file: 06_drilling/j0112circle.inp

Drilling is a technique encountered in several crafts, such as carpentry and marble crafts, to create tubular holes in the material. Drills may be hand and electrically powered.

Drilling is similar to turning but in this case, the material is constrained in place and the tool is rotating. The underlying mechanism that rotates the tool is based on the wheel and axle simple machine. The drilling mechanism is based on the wedge simple machine.

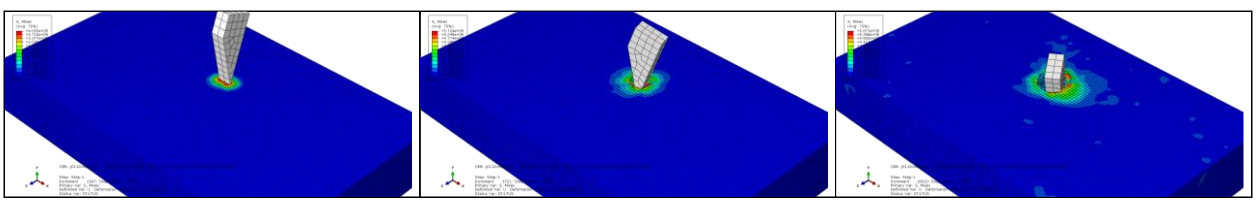


Figure 7. Simulation of material drilling.

5.2.2 Add

http://vocab.getty.edu/page/aat/300229467 - <additive and joining processes and techniques>

Additive actions regard the assembly of structures. The simulation models focus on the forces that are used to place the added materials and the stability of the result.

The mechanisms used to model assembly are governed by the forces needed to place an assembled piece in place. The stability of the assembly is governed by gravity and the tension forces existing in the assembly[16].

The mechanism that governs the instability of an assembly is the lever, in that when a piece in contact with another body is pulled down by gravity it will either stay in place or not. In the latter case, the unstable piece forms a lever with its supporting one, resulting in a rotational motion as it falls.

5.2.2.1 Assembly

http://vocab.getty.edu/page/aat/300053007 - assembling (additive and joining process)

Simulation input file: 07_assembly/Job-1.inp

The underlying principle in the successful assembly of built structures without adhesives (i.e. glue, mortar etc) is the stability of the whole that is made of parts. The physical law that governs this stability is that the gravity vector initiating through the centre of mass of each piece should intersect its supporting surface; if this condition is met then the piece is stable, otherwise, it shall fall. When a piece falls, its fate is determined by the location of other pieces, as well as the momentum it has gained during its fall.

To comprehensively illustrate this archetypal mechanism, a Jenga-like simulation is presented. The following archetype regards an unstable assembly and predicts the stability of the instability of the built structure. In this case, the structure's fate is governed by gravity.

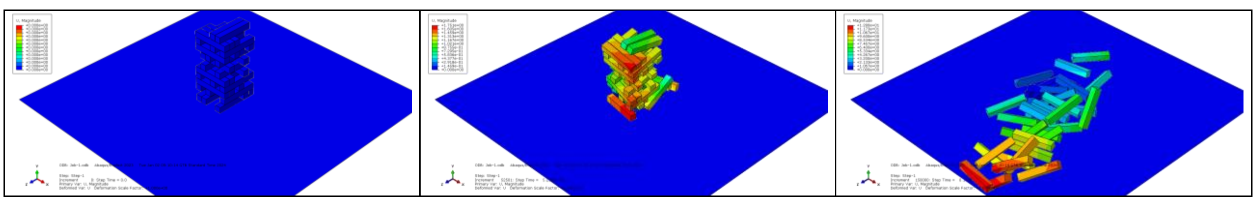


Figure 8. Simulation of assembly instability.

5.2.2.2 Filling

http://vocab.getty.edu/page/aat/300053092 - filling (process)

Simulation input file: 08_filling/Job-1.inp

To counter the effect of gravity and increase the stability of assembled structures adhesive material is inserted between pieces, such as the application of glue or mortar. The adhesive material exhibits high plasticity when applied. Waiting time is required for it to dry and be able to sustain the tension required for holding pieces in place.

[16] It is noted that screws, bolts, and nails are also used for the stability of assemblies. However, these are classified under the interlock archetypal simulators.

The stability of the overall structure is determined by several factors, about the adhesive properties of the filling material and to the density of the pieces (which determines their weight). The archetypal simulation below illustrates the tensions developed in a brick wall due to its weight and the sustainability of the structure due to the use of mortar.

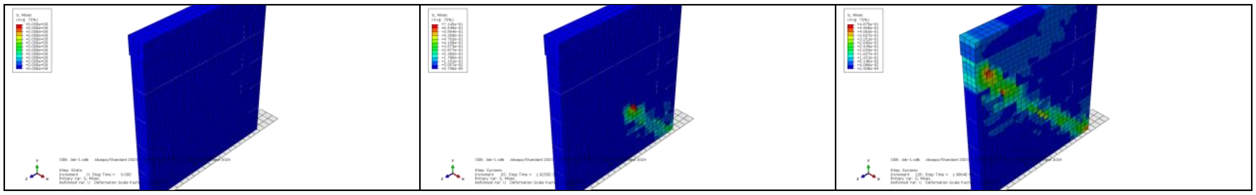


Figure 9. Simulation of assembly stability.

5.2.3 Interlock

http://vocab.getty.edu/page/aat/300229467 - <additive and joining processes and techniques>

Interlocking uses forces to store potential energy in the construction. This energy is stored in the interlocked components because of the forces involved in maintaining their relative positions.

5.2.3.1 Fastening

http://vocab.getty.edu/page/aat/300053015 - fastening

Simulation input file: 09_fastening/Static_Preload.inp

Fasteners are components used to join or connect two or more parts. They hold components in place, creating a stable assembly. Fasteners are mainly screws, bolts, and nails, while they are very often accompanied by nuts and washers that increase friction and hold them more securely in place.

Driving forces that insert pieces into existing assemblies store potential energy using elastic deformation, compressive and tensile forces, frictional forces, and mechanical interference to interlock pieces in place. The archetypal simulations below illustrate two cases. Both simulations regard the same configuration of bodies: a horizontal beam that is fastened perpendicularly into a vertical beam.

In the first simulation, the assembly is stable, that is the fasteners are strong enough to hold the horizontal beam in place and sustain the effect of gravity. The illustration is zoomed in on the fasteners to show the tension withheld by them.

In the second simulation, an additional vertical load is applied on the horizontal beam, causing the deformation of the structure. The illustration is zoomed out to show the deformation.

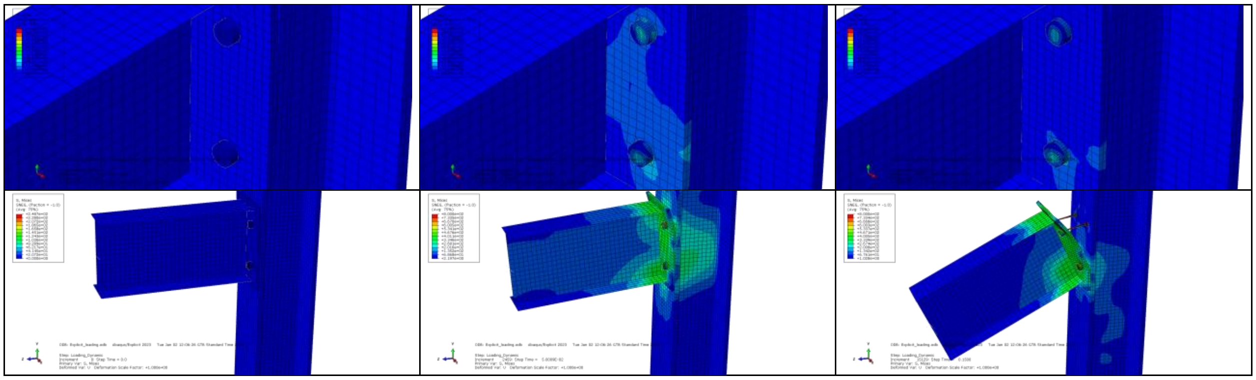


Figure 10. Simulation of fasteners. Top: secure structure. Bottom: deformed structure.

5.2.3.2 Swivelling

Link: http://vocab.getty.edu/page/aat/300434215 - swivels[17]

<u>Simulation input file:</u> 10_swivelling/Job-2.inp

Swivelling refers to the act of rotating or turning around a fixed point or axis, based on the wheel and axle simple machine. It involves connected components that rotate around an axle, enabling the flexibility of the composite structure. For example, in jewellery-making the mechanism that makes a necklace flexible is the cord that passes through the jewels' holes. The simple machine that governs this mechanism is the wheel and axle. Other examples can be found in the blacksmithing of hinges that enable the swivelling of doors, or in the woodworking of windmills and wooden gears that enable rotational movement.

The connected parts are referred to as "lugs". When lugs are joined using a bolt in a way that allows them to rotate freely, this operation is often referred to as a "pivot" or "swivel" connection. The term "swivel" implies the ability of the connected parts to rotate around the axis of the bolt. This type of connection is common in various mechanical applications where rotational movement is desired, such as in hinges, joints, or other assemblies where flexibility or rotation is required.

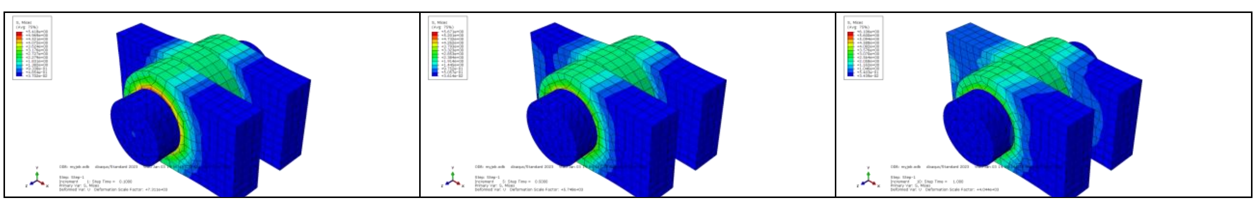


Figure 11. Simulation of swivelling.

[17] The Getty Arts and Architecture Thesaurus does not contain a verb for swivelling. As such, an SKOS entry has been authored for the Craeft Authoring Platform. Due to this lack, we have added the corresponding noun here from said thesaurus.

5.2.3.3 Tying, weaving, and knitting

http://vocab.getty.edu/page/aat/300053026 - tying

http://vocab.getty.edu/page/aat/300053642 - weaving

Link: http://vocab.getty.edu/page/aat/300053634 - knitting (process)

Simulation input file: N/A.

To model the composition of fabrics we used the TexGen simulator. As mentioned in Section 2, TexGen models the geometry of textile structures. TexGen allows for detailed geometric modelling given definitions on the weft and knit. Using the created models, we can understand and predict fabric appearance and behaviour under different conditions. The process of modelling fabrics regards the selection of textile parameters, the geometric modelling, and the setup for simulations. The latter regards the composition of models that can be imported into the Simulia Abaqus simulator, to predict mechanical properties of fabrics, such as sensitivity to stretching, point of rupture etc.

Below we provide examples of textile composition using the TexGen tool. The simulated structures can be exported in multiple formats so that their behaviour and appearance as textiles can be simulated.

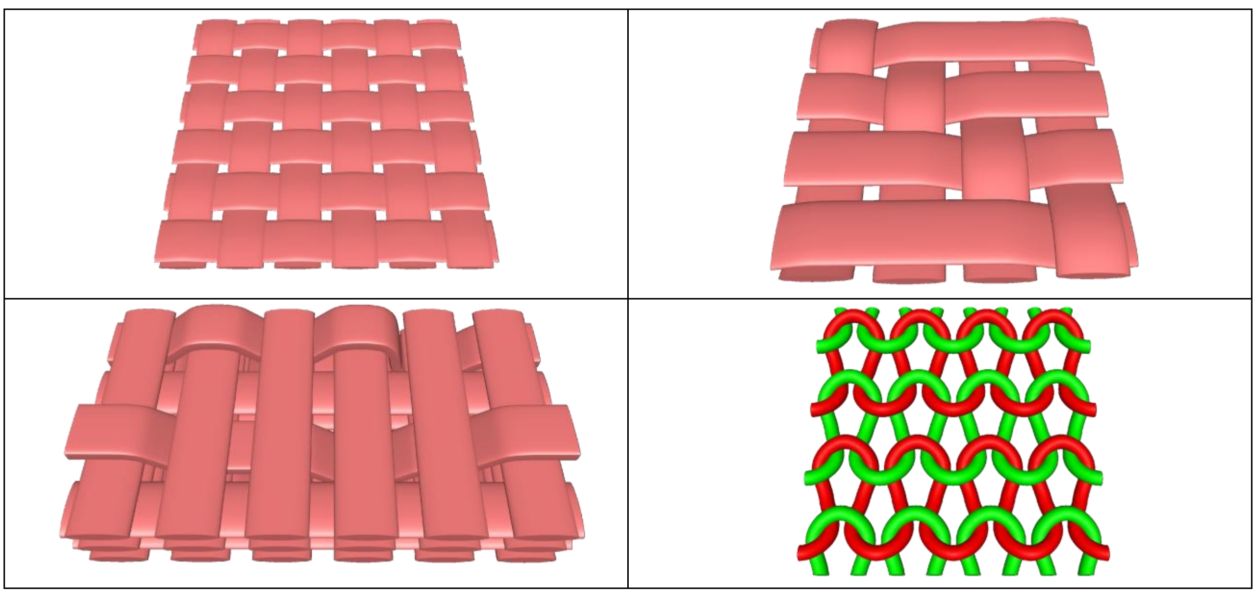


Figure 12. Three weaved and a knit fabric structure created using TexGen. Top-left: plain-weave; Top-right: satin-weave; Bottom-left: arbitrary weave for creating patterned textiles; Bottom-right: knitted structure.

5.2.4 Freeform

http://vocab.getty.edu/page/aat/300053098 - forming (physical activity)

Freeform transformations depend on the plasticity of the material, which is often induced by heat or humidity. Pressure forces and the shape of the tool that applied them play a central role in the result. Depending on the density of the material gravity (or self-weight) can play also a role in the result.

In some cases, heat is used to facilitate the process, as it increases the viscosity of some materials.

The relevant material properties are the plasticity of the material, as well as its elasticity which determines if the debossed pattern will remain debossed or if the material will reassume its original shape.

5.2.4.1 Bending

http://vocab.getty.edu/page/aat/300053101 - bending

Simulation input files: 11_bending/Bending.inp, 12_bending/Job-1.inp

Bending is used in several crafting actions when plastic materials are employed. In traditional crafts, examples are found in basket weaving, blacksmithing, woodworking, and boat building and, in general, in cases where pressure is applied to form plies of material without breaking them. The bending of materials is achieved with simple tools and is based on the lever simple machine. The simplest case of bending requires at least three points of pressure, while variants can employ one point of encasement and two points of pressure. In all cases, two levers can be identified in the mechanism.

Two archetypes are implemented, differing in the type of material damage. The first regards a ply of material that exhibits high plasticity, such as a piece of wood that has been steamed. The second regards a stiffer material and, in this case, a damage model is employed to simulate the non-linear deformation that the material undergoes under pressure.

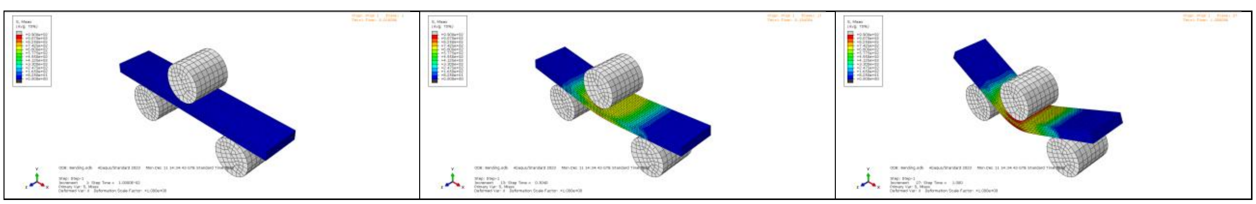


Figure 13. Simulation of bending a material.

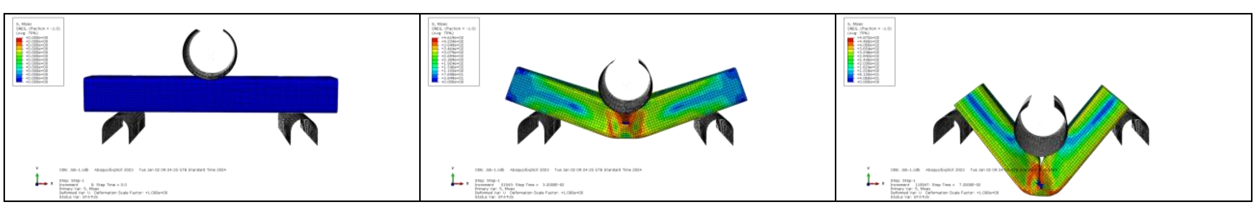


Figure 14. Bending simulation

5.2.4.2 Moulding

http://vocab.getty.edu/page/aat/300053134 - moulding (forming)

Simulation input files: 13_moulding/CEL_BOTTLE.inp

In glasswork, the moulding process is used to create hollow bodies. In this case, the parison is then put into a mould cavity, which is typically two halves that shall form the shape of the hollow body. The mould closes around the parison. Either compressed air (blow) is blown into the parison or an internal mould is used, to inflate or deform the parison, respectively. Due to this pressure, the parison takes the shape of the mould. The pressure forces the molten glass to conform to the mould's shape, creating a hollow body.

The archetype below illustrates this operation, for the case of pressure created by the insertion of an internal mould.

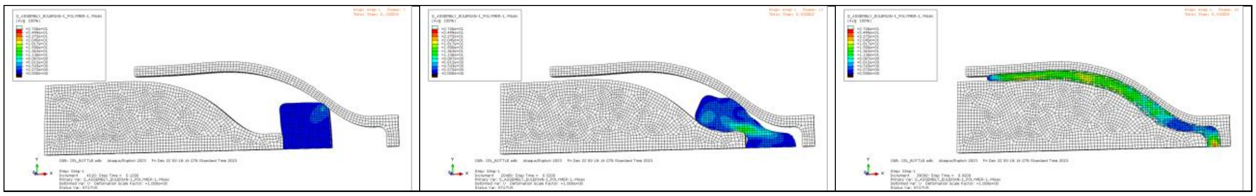


Figure 15. Simulation of forming a hollow body by a moulding process.

5.2.4.3 Debossing

Debossing is the process of creating recessed relief images and designs in materials. A debossed pattern is sunken into the surface of the material and, depending on the thickness of the material might protrude on the reverse side.

The action type according to the standardised vocabulary is: http://vocab.getty.edu/page/aat/300265527 - debossing

Simulation input files: 14_debossing/j300_deg60.inp

The depth dimension is such that does not cause damage or rupture to the material, such as breaking or cracking. The simple machine that corresponds to this action is the lever which is typically used in debossing presses.

The archetype features a tool of arbitrary shape, in this case, instantiated as a rod with a hemispherical endpoint, to compress the material.

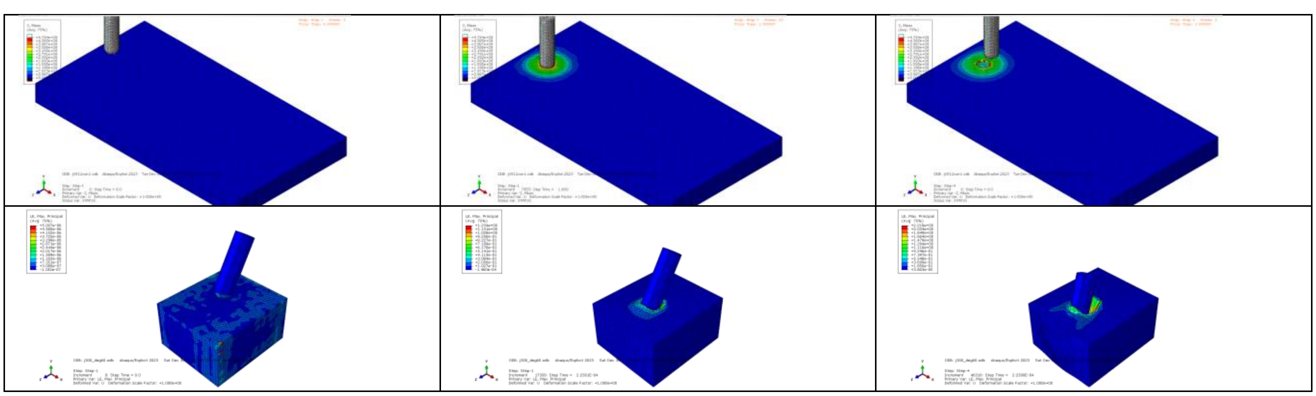


Figure 16. Simulation of debossing.

5.2.4.4 Wheel-throwing

http://vocab.getty.edu/page/aat/300053908 - throwing (pottery technique)

http://vocab.getty.edu/page/aat/300257611 - blocking (surface marking)

Simulation input files: 15_wheel_throwing/xaxis.inp

Wheel-throwing is mainly encountered in pottery but mechanically similar actions are met in glasswork (blocking). The action is similar to the turning subtractive action but, in this case, the material is highly plastic. Thus, the operation instead of removing material deforms the shape of the rotating material, while preserving its mass.

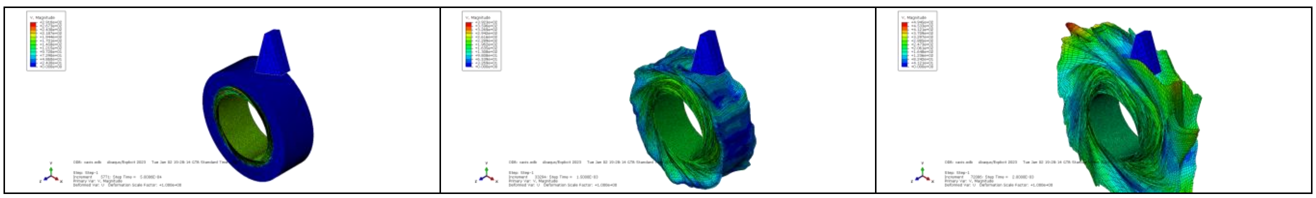


Figure 17. Freeform shaping of a plastic material.

5.2.4.5 Twisting

http://vocab.getty.edu/page/aat/300072926 - torsional stress

Simulation input files: 16_twisting/s_dJob-1.inp, 16_twisting/Job-2.inp, 16_twisting/Job-3.inp, 16_twisting/Job-4.inp

Twisting refers to the action of developing torsional stress by a turning motion of a solid body about its axis of symmetry. Twisting is a fundamental technique found in various crafts, prominently used to add strength, aesthetics, or functionality. Examples can be found in the spinning of fibres together to make yarn or thread, in basketry where willows are twisted into threads and in ropemaking where strands are twisted to create ropes or cords.

The physical properties of importance are the plasticity and elasticity of the material, which determine the stress that will be developed in the material and if it will regain its original shape or on. In turn, these determine the stiffness of the final product, for example, if it is a fibre turned into a thread how stiff will be the resultant fabric made out of it. Depending on the material, its damage properties determine how much the material can be twisted until it breaks.

In the examples below, the twisting of a ply of material is studied. Twisting occurs by a circular actuator, which is visible on the right part of the images. In the first row, it is twisted by two full circles, in the second row by four circles, in the third row by eight circles, and in the fourth row by sixteen circles. We observe that while in the first row, the material is symmetrically distorted, as the twisting increases this symmetry is not retained and the material is distorted in a non-uniform fashion. When twisting increases and mechanical strain grows, we observe damage to the material (shown in detail in the zoomed-in images).

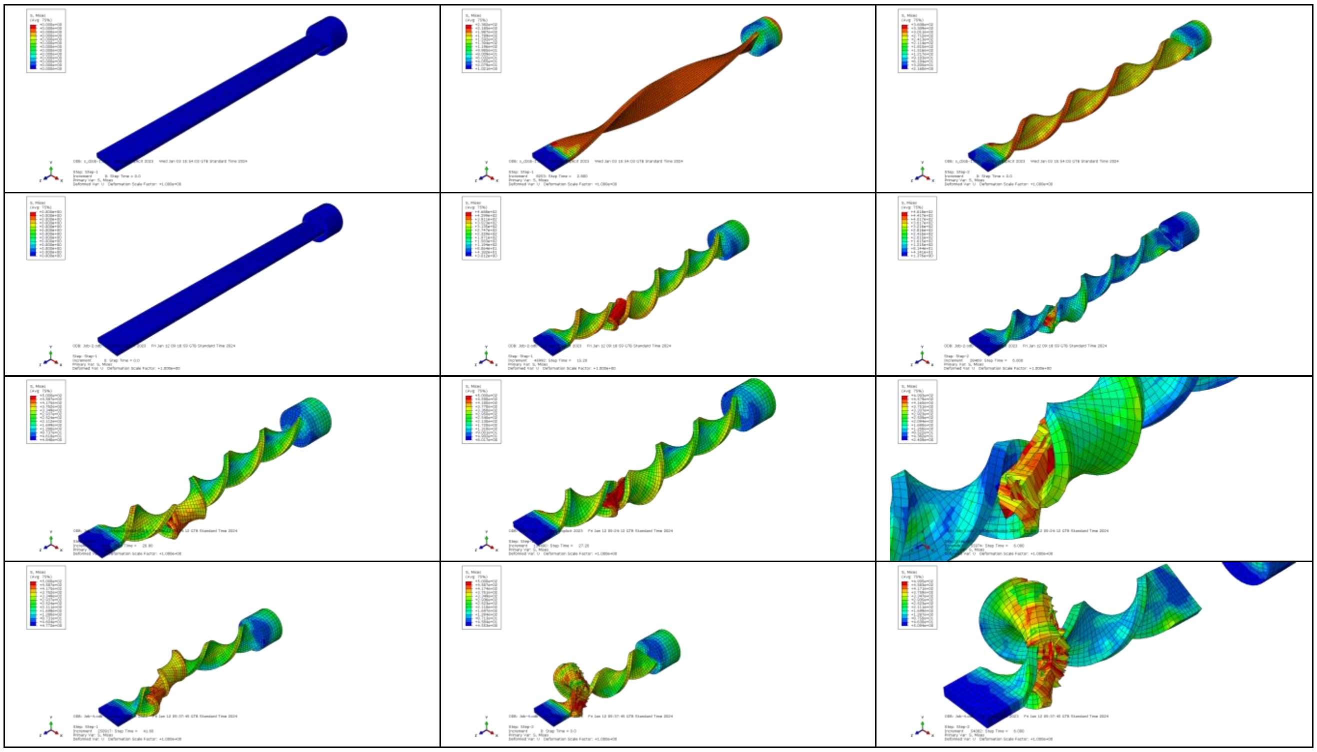


Figure 18. Twisting a ply of material multiple times.

The examples above are indicative of the value of performing realistic simulations. While in a simplified simulation, we would expect that the material would be twisted uniformly, by simulating with realistic parameters we can predict the limits of the action and a more accurate result.

5.2.4.5. Hot-rolling

http://vocab.getty.edu/page/aat/300137949 - hot-rolling

Hot-rolling is a method of semi-forming molten metal into long shapes narrow in cross-section, such as rods or sheets. The material is passed between dual rollers revolving in opposite directions at a uniform speed. The metal is heated to increase its plasticity.

The simulation involves the simultaneous rotation of the rollers as well as the definition of a friction coefficient that enables the motion of the material through the rollers. The example demonstrates also the compatibility of the simulations as the rolled piece of material is the result of the cutting process in Section 5.2.1.1; that is, one of the two pieces resulting from the cut. The realism of the simulation can be observed in the distortions of the cut piece which are intonated as the piece passes through the rollers. The resulting piece becomes straight and thinner. To further indicate the compatibility of simulations, we note that the rolled piece is the piece of material used in the second engraving example of Section 5.2.1.2 (see Figure 3. **Simulation of a carving action with a numerically defined trajectory.**).

The affordance to be mentioned here is that this process can be applied only in ductile materials (i.e. metals); it cannot be applied to pieces of wood. Moreover, temperature is required to achieve plastic behaviours with a reasonable amount of pressure.

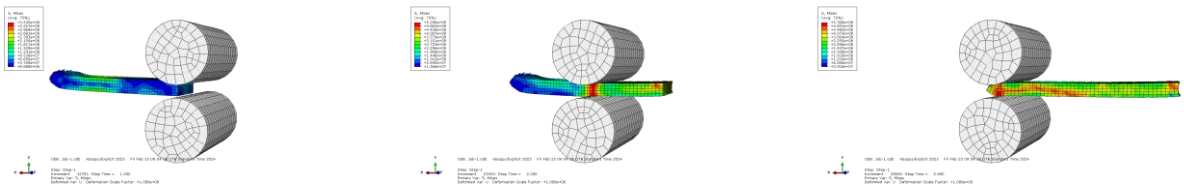


Figure 19. Hot-rolling of a piece of metal.

5.2.5 Composite simulations

Using the simulation archetypes as individual steps it is possible to compose more complex simulations that mimic sequences of practitioner actions.

The example below combines four carving actions to create a cross pattern on a piece of material. The simulation mimics the motion of a carving tool operated by a practitioner to sculpt the material. At each carving stroke, the tool creates a ridge, which is then retracted and pushed to remove the carved piece from the surface. The tool is then translated and rotated appropriately and the action is repeated to create the pattern.

<u>Simulation input file:</u> 17_composite_carving/j0112circle.inp

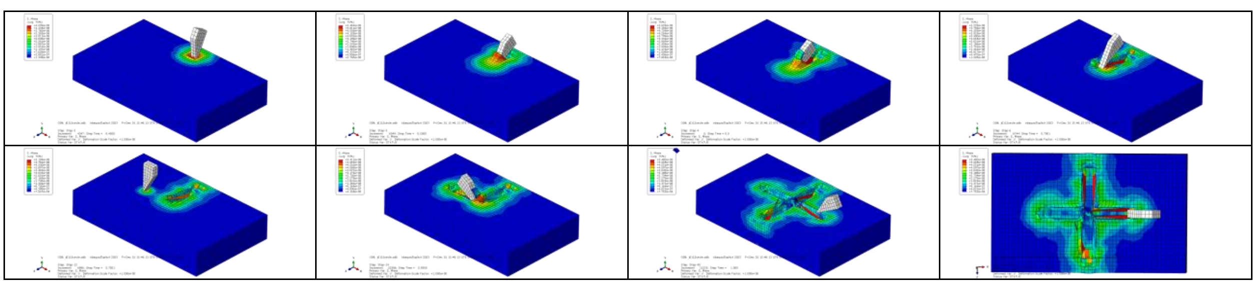
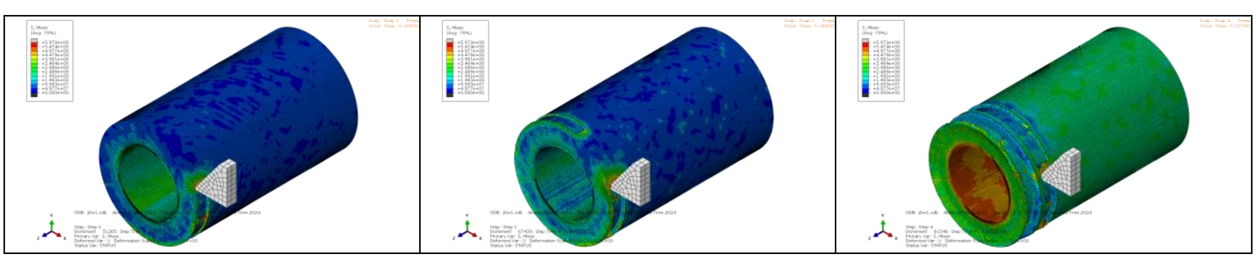


Figure 20. Composition of carving actions.

The next example uses the turning archetype to create a striped pattern on a piece of material. The turning action that carves material is repeated to create a symmetric composition.



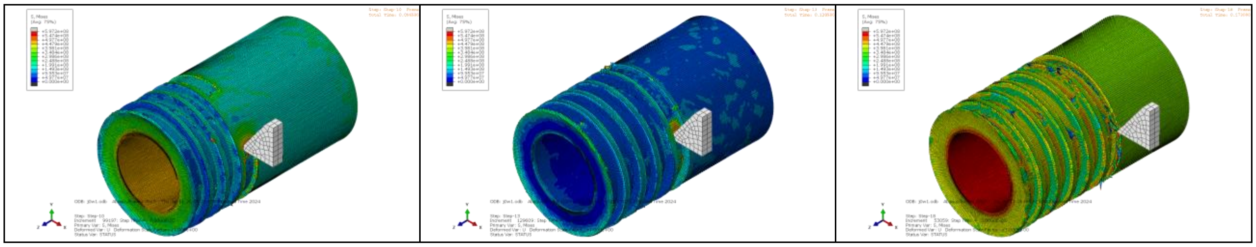


Figure 21. Composition of turning actions.

The next example illustrates a composition of diverse actions demonstrated in this deliverable. The main actions of this process are the following:

- First, a piece of metal is cut from a bulk of material. This is the simulation archetype shown in Section 5.2.1.1.
- Then this piece of metal is repeatedly passed through two parallel and simultaneously revolving cylinders until it is thin enough to form a metallic sheet. This is demonstrated in Section 5.2.4.5.
- Then the sheet is engraved with a pattern. The engraving tool will carve a sinusoidal shape on the surface of the material. This is demonstrated in Section 5.2.1.2.
- The sheet is finished by trimming its edges with a cutting tool to form an arrow-like shape.

Nevertheless, several intermediate and auxiliary actions take place in between, such as:

- Waiting after the rolling step for the piece to cool down so the practitioner can touch it. In this case, the heat diffusion and temperature are simulated, using the facilities of Simulia Abaqus.
- Placing the piece on a stable position on the engraving table and moving the piece back to the cutting. In this case, gravity is simulated to predict how the piece is going to be stabilised on the processing surface.

The process definition is the following.

- Step 1. Cut a piece of metal striking it with a wedge-shaped cutting tool on a cutting table. Schema: strike, then check if the metal is cut. If not, repeat.
- Step 2. Move the cut piece from the cutting table to the rolling machine.
- Step 3. Measure the thickness of the piece and decide how many times it should be rolled to be reduced to the intended thickness. The underlying constraint here is that we cannot thin the material piece arbitrarily but we have to gradually thin it. Roll as many times as decided.
    - Step 3a. Adjust roller distance
    - Step 3b. Place the piece in front of the rollers and align it with them.
    - Step 3c. Put the rollers in motion.
    - Step 3d. Collect the thinned piece.
- Step 4. Wait until the piece cools down and you can touch it. Schema: active waiting.
- Step 5. Engraving is based on the debossing technique. This step may require multiple strokes depending on the pattern. In this case, a single line of sinusoidal shape is drawn and, thus, a single drag on the material is required. Engrave a shape on the piece.
- Step 6. Move the piece back to the cutting table.
- Step 7. Finish the piece by cutting its four edges.

- Cut edge 1
- Cut edge 2
- Cut edge 3
- Cut edge 4

The workflow of the process is shown in the diagram below.

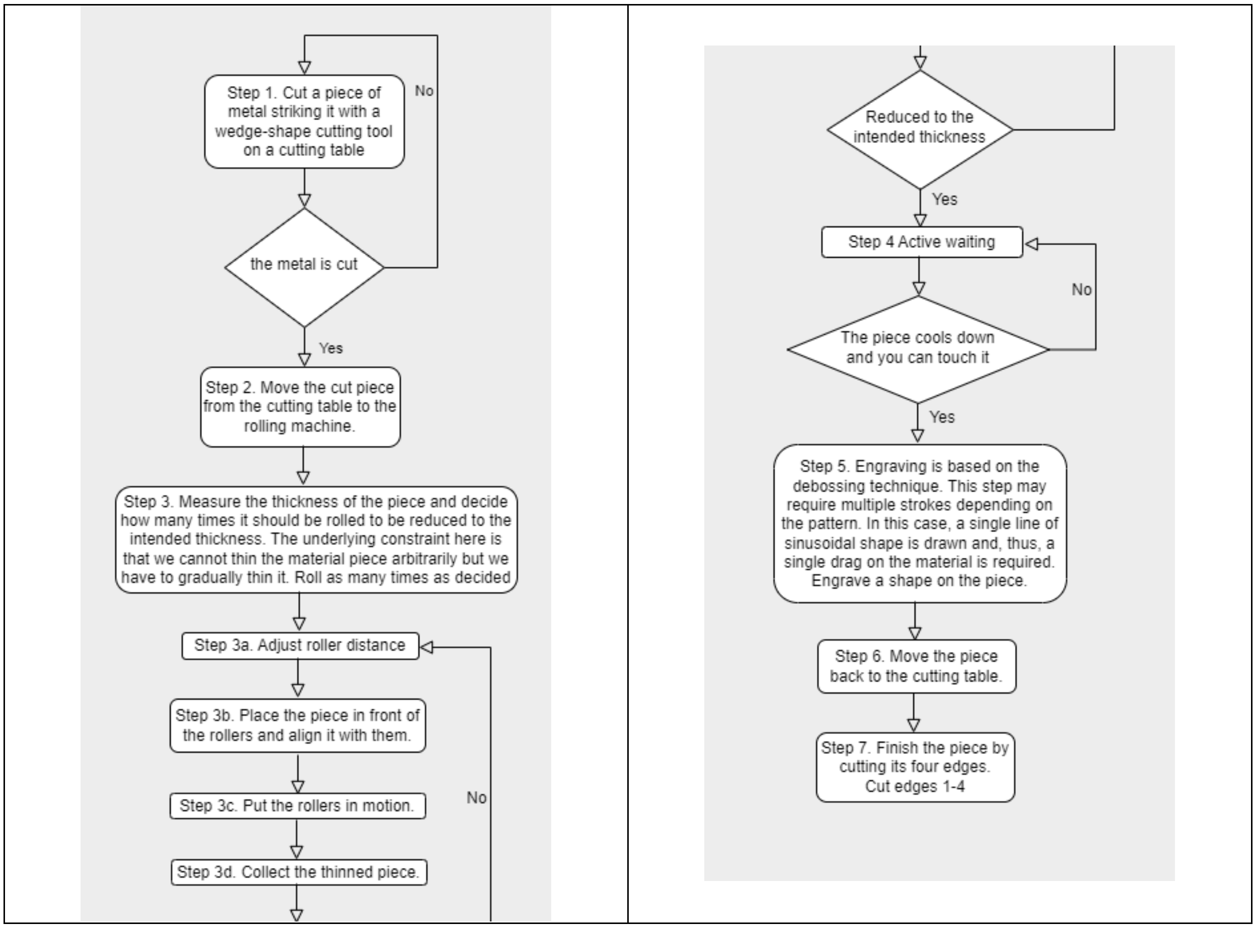


Figure 22. A flowchart of a composite process simulation using archetypal action simulations.

In the following figures, we show the results of the simulations that have not been shown in the previous examples. The figure below illustrates the placement of a piece on the cutting table, by simulating gravity.

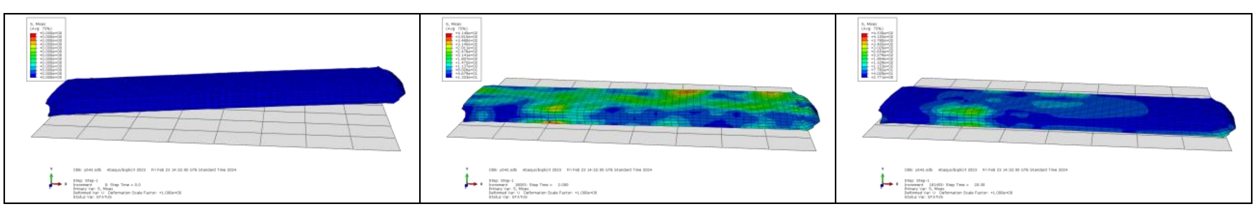


Figure 23. Placing a piece of material on a surface until it stabilises due to gravity.

In the following figure, the finishing of the part into an arrow-shape results using four cuts is shown.

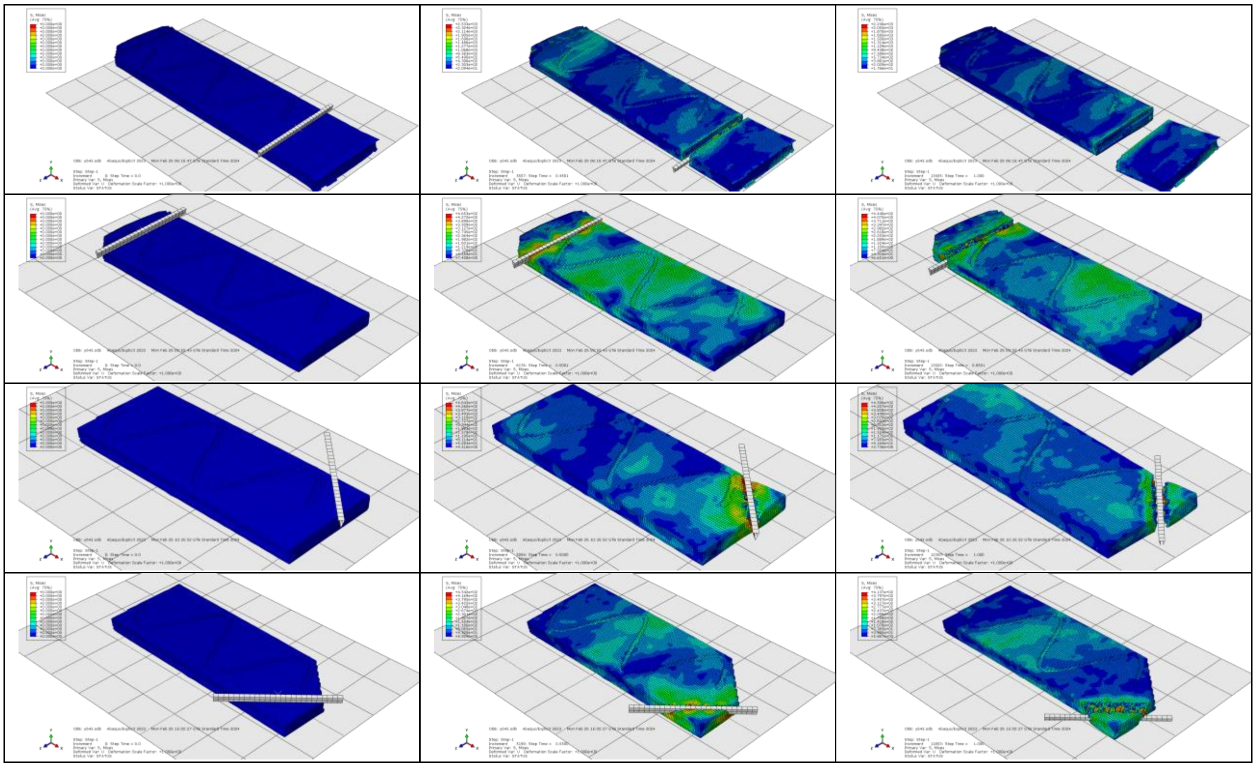


Figure 24. Finishing a piece of material on a surface using four cuts (each row corresponds to a cut).

The final piece at rest due to gravity and its rendering as a metallic part is shown in the figure below.

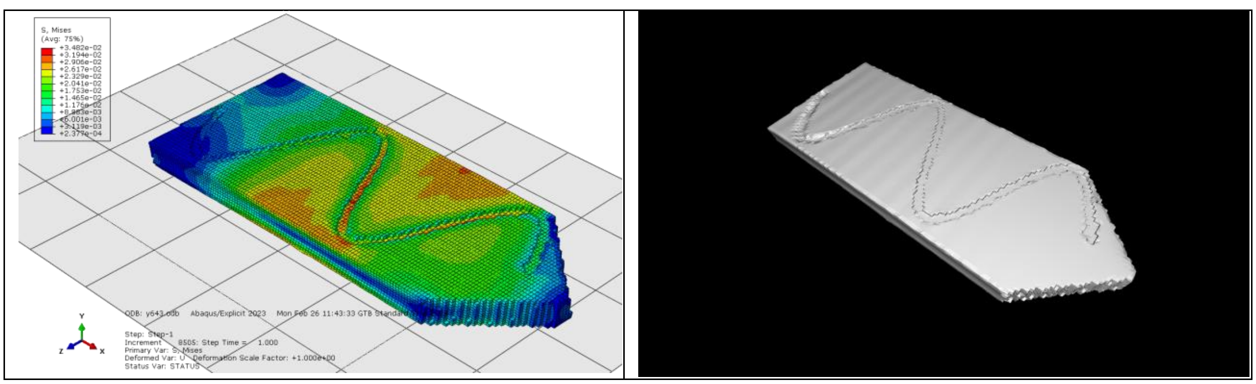


Figure 25. The resulting piece is at rest and it is rendered as a metallic object.

5.2.5 Discussion

The simulation archetypes presented in this section are intended to serve a dual purpose:

This first is to provide “templates” of craft-specific action simulators. These templates are generic as to the material properties and models, as well as to the pose and shape of the objects in the simulations. In other words, the material properties and models can be changed so that the same action is simulated for different materials and practitioner motions. Moreover, the shape of tools can be directly substituted with more specific ones, pertinent to the specific craft action to be simulated.

The second is to comprise the building blocks of craft-specific process simulators. The last subsection of this section (5.2.4) demonstrated the potential of composing sequences of actions. This will be in the future employed by the Craft Studio and the Design Studio for the training of practitioners and the design of new craft products.

6 Visualisation

Accelerated by GPU hardware, the real-time rendering of Lambertian, “matte”, or “diffuse” surfaces is commonplace in modern Computer Graphics. The real-time rendering of shiny, transparent, and translucent materials from their geometric models remains a challenging problem. Modern rendering pipelines achieve approximations, but the accurate simulation of the interaction of light with materials requires significantly more computational resources. For real-time rendering, the simulation results are integrated with the Unity rendering pipeline.

6.1 Toolbox

Material-specific rendering and realistic inclusion of challenging materials as well as the inclusion of optical effects occurring during light transportation, i.e., diffusion, reflection, absorption, and diffraction, require PBR and are provided by offline rendering using Mitsuba 3. As this infrastructure requires middleware programming, a wrapper was developed that simplifies its use. This toolbox [53] interprets human-readable configuration files in JSON format that define the scene or event to be rendered. These files can be authored by humans or generated by a scene-authoring graphical user interface (GUI).

The toolbox hides the complexity of programming and enables the rendering of a static scene by defining its elements at a given moment in time. These elements are the objects, light sources, and the virtual camera imaging the scenes, as well as the individual properties of each element. This way, we can realistically render artefacts from any material and predict their appearance when placed in an arbitrary environment and imaged from a specific viewpoint and sensor. The rendering result for a scene is an image. Dynamic scenes are treated as sequences of static scenes and result in video.

The rationale for providing access to the aforementioned functionalities through a configuration file is the following. The content of this file can originate from a recording, a physics-based simulation, or the log of an interactive simulation. The toolbox is utilised as a “compiler” that receives configuration source files and outputs visual media. The benefit is that multiple types of applications are interfaced with the toolbox by generating the configuration files needed and receiving the rendering results as images or video.

6.2 Scene Setup

Objects are added to the scene by importing files with their geometry and material properties in Wavefront OBJ (.obj) or Standford PLY (.ply) formats. When importing third-party data, e.g., from repositories, scale and pose transformations are needed to align reference coordinate frames and metric systems. Objects may be textured, and, in that case, the texture coordinates are required to be included in the mesh. The mesh filename, along with any accompanying transformation, is defined in the configuration file.

Materials are described through their Bidirectional Scattering Distribution Functions (BSDFs) [54], which characterises how incident light is scattered by a surface. The visualisation toolbox provides access to Mitsuba 3 and contains a library of preset BSDFs, while additional materials can be photographically measured as in Ref. [55].

Additionally, surface roughness is defined as a material property, although it regards the shape of an object. Modelling structures at this scale is not possible for objects of the size of our workpieces. Surface roughness is modelled and rendered using diffraction properties instead of modelling the shapes of microstructures, as in Ref. [56].

Illuminating the virtual scene is supported in two ways. The first is to explicitly define light sources and define their size, shape, location, orientation, as well as their radiance spectrum and intensity. The second employs a High-Dynamic-Range Imaging (HDRI) map to simulate the lighting of specific environments. The HDRI map captures a view of a location in all directions from a single viewpoint. Moreover, the pixel brightness values are not limited by the dynamic range of the sensor and match real-world lighting values. HDRI maps are acquired using a 360° HDRI camera or downloaded from online libraries.

Each frame is rendered in an image acquired by a virtual camera. The viewpoint of the camera is defined by its location and orientation or, otherwise, its extrinsic parameters. The intrinsic parameters of the virtual camera define its field of view and resolution. An additional parameter determines rendering quality, providing quick and rough renderings for testing and high-quality renderings at a greater computational expense.

6.3 Offline Use

Two types of output video are supported. The first presents static 3D models, and the camera follows a circular trajectory around the object. The first is useful for creating videos that show artefacts from multiple views. In the second type, a sequence of scenes is provided as separate 3D files and used to render animations that represent crafting actions through simulation or recording. This type of video is useful for visualising crafting actions.

The toolbox can be integrated with other software using file communication. Specifically, it reads the configuration file and outputs an image or video. The 3D models of objects are retrieved from files and defined through their filenames in the configuration file. Object animations are stored in sequences of 3D models. Each object and each object part are stored in individual files and individual sequences. The files are indexed through a naming convention, although this complexity is transparent for the user.

6.4 Online Use

In Ref. [52], offline simulation is used in real-time by parameterising actions as to their execution parameters and pre-computing the results. The simulation results are stored in a hashtable, which enables the rapid retrieval of the simulation result corresponding to the specific action parameters used. This approach is extended in this work by adding to the parameters of the viewing pose, increasing complexity by the 6 DOFs required to represent the viewing pose.

On the other hand, the storage capacity is reduced because this time only images are stored instead of simulator result files, which are cumbersome because they contain 3D meshes. Moreover, in practice, the viewing-pose space is limited given the ergonomy of the task and the body pose needed by the practitioner to execute it.

6.5 Discussion

The toolbox is designed as middleware that can be used by a GUI or a third-party application that creates the configuration files and collects the results from the toolbox. Our motivation for this design choice is to enable the rendering of scenes from multiple types of sources. The toolbox is accurate but does not operate in real-time. It provides high-quality renderings that contribute to an interactive design process that enhances creativity and ensures that the final product meets the desired aesthetic and functional requirements. For interactive simulations, less accurate rendering approaches are recommended to meet real-time requirements. Nevertheless, the logs of real-time interaction can be stored and re-rendered offline in higher quality.

7 Real-Time Simulation and Visualisation

We present results relevant to the crafting and presentation of artefacts. A wide spectrum of situations is considered to assess the capabilities and suitability of the supported simulation and rendering methods in the context of craft action and product presentation.

The specifications of the computer used in the experiments are as follows: Central Processing Unit (CPU) × 64 Intel i7 8-core 3 GHz, RAM 64 Gb, GPU Nvidia RTX 8 Gb RAM (RTX2060 SUPER), Nvidia, Santa Clara, CA, U.S., solid-state drive (SSD) 256 Gb, and hard disk drive 2 Tb. On this computer, the longest-duration offline simulation lasted less than 7 hours, while real-time simulations and renderings are performed at 80 fps. For PBR, images are rendered at a 1024 × 1024 resolution, with the most demanding rendering duration being less than 2 min.

In this subsection, the results of real-time simulations combined with real-time visualisation are presented. Each simulation result is a sequence of 3D meshes representing the scene surfaces at each frame of the simulated time interval. In addition, the results of real-time visualisation are compared with the renderings of the visualisation (section 5.1.5). Thus, each real-time simulation result is rendered twice. In Figure 26. Real-time and offline renderings of clay throwing.-Figure 28. Renderings of three moments of a woodturning activity using a steel gouge in temporal order from left to right., online rendering results are shown in the top row, while offline renderings in the bottom.

In Figure 26. Real-time and offline renderings of clay throwing., simulated pottery clay throwing is presented. The action is the shaping of the clay using hand gestures. The user adds and subtracts material when the clay is wet. The benefit of realistic appearance simulation is observed when the first row is compared to the second. Shadows are simulated in both conditions, but the real-time approximation lacks the clarity of PBR, obstructing shape comprehension as the human visual system is highly attuned to the subtle variations in shadow intensity and uses them to infer shape [57].

Figure 26. Real-time and offline renderings of clay throwing.

Figure 27. Renderings of a glass shaping action using a pair of steel jacks and a wooden battledore in temporal order from left to right. Shows instances of a glassblowing simulation. In the simulated activity, a pair of "jacks" are used to form the neck of a glass vessel. At the same time, a "battledore" is used to constrain, or "block," the shape of the rim of the vessel. The 3D models of the battledore and jacks were retrieved from [58,59], respectively. The tools are manipulated in real-time using two independent UI controllers.

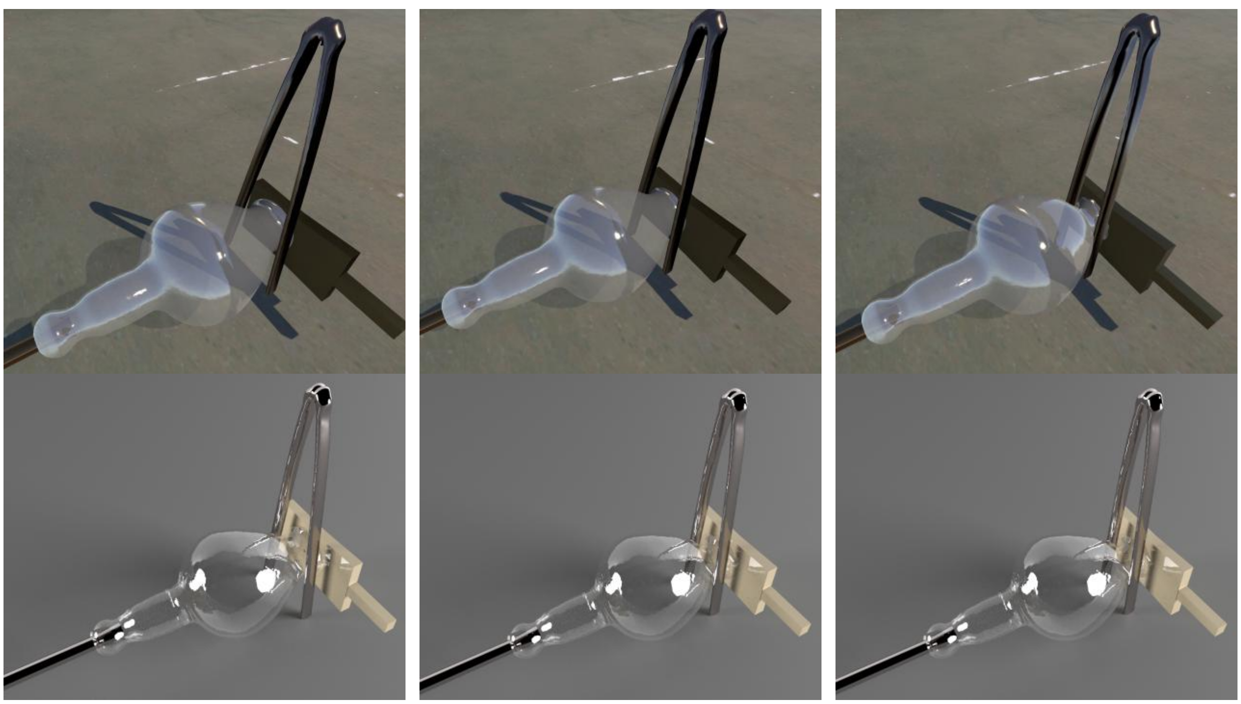


Figure 27. Renderings of a glass shaping action using a pair of steel jacks and a wooden battledore in temporal order from left to right.

The real-time simulation of semi-molten glass approximates glass plasticity by using its plasticity value at working temperature (≈1100–1200 ◦C). As in Figure 26. Real-time and offline renderings of clay throwing., real-time rendering approximates the appearance of transparent and shiny material. Offline rendering captures the diffraction better, as well as the scattering of light due to its transport through the glass and the specular highlights produced on its surface. These phenomena are visual cues to 3D shape perception of transparent and glossy surfaces [60,61], facilitating a more accurate perception of glass body shape.

In Figure 28. Renderings of three moments of a woodturning activity using a steel gouge in temporal order from left to right., woodturning on a lathe is simulated. A gouge is used to subtract material and create a honey dip. The user manipulates the location and orientation of the gouge in real-time. Given that the raw wood surface is matte, specular highlights do not occur and shadows are well simulated. Thus, both real-time and offline visualisations offer sufficient cues for accurate shape perception. However, the real-time simulation is limited in that the voxel-based deletion of material does not simulate the fate of the removed wooden chips, which may be potentially projected into space after their carving. This is relevant to the safety aspects of the simulated tasks, which are not covered here.

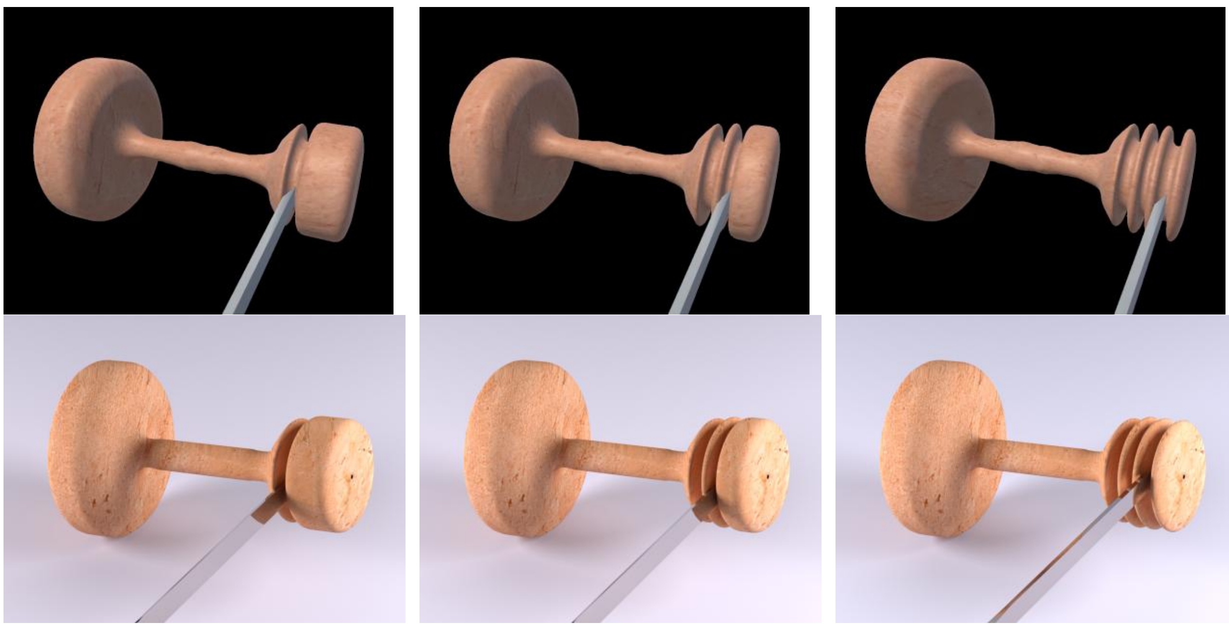


Figure 28. Renderings of three moments of a woodturning activity using a steel gouge in temporal order from left to right.

8 Photorealistic actions

In this subsection, we present the results of offline simulations from the integration of an FEM simulator with our visualisation toolbox. The results are presented and classified into the three elementary actions, as instantiated from the corresponding simulation templates in Ref. [52].

8.1 Subtractive

The central mechanism in subtractive actions is the wedge Simple Machine. At its edge, a wedge concentrates the force applied to its face, facilitating the creation of stress at its impact area. When this stress is higher than the yield or damage threshold of the material, then it deforms or breaks. This is illustrated in Figure 29. Carving a wooden block with an iron wedge., where a wedge-shaped metallic chisel is used to carve a chip out of a block of wood. Based on the orthotropic model, wood's elasticity and plasticity are characterised in three principal directions, namely longitudinal (L), tangential (T), and radial (R). Wood is modelled using nine independent elastic constants. These include (a) three elastic moduli E_R, E_T, E_L for longitudinal, tangential, and radial directions, respectively, (b) three Poisson's ratios v_{RT}, v_{RL}, v_{TL}, describing the coupling between strain in one direction and stress in another, and (c) three shear moduli GRT, GRL, GTL for shear deformations in the respective planes. In the example, the wood of Norway spruce (Picea Abies) is simulated using the following parameters from [62]: E_R = 830MPa, E_T = 545MPa, E_L = 12,000MPa, v_{RT} = 0.42, v_{RL} = 0.02, v_{TL} = 0.02, G_{RT} = 55MPa, G_{RL} = 500MPa, and G_{TL} = 550MPa. The workpiece was composed of 742K elements, and the simulation lasted 6.8 h for 200 frames.

Figure 29. Carving a wooden block with an iron wedge.

In Figure 30. Four instances of a woodturning simulation in temporal order from left to right., the woodturning example from Figure 28. Renderings of three moments of a woodturning activity using a steel gouge in temporal order from left to right. Is revisited to indicate the benefit of realistically simulating material damage. The material properties of wood were the same as above. The leftmost image shows an overview of the simulated scene. The two images in the middle focus on the interaction of the tool and material and the initiation of wooden chip creation at the carving location. The rightmost image illustrates the projection of these chips into space and the corresponding safety threat. To avoid this threat, woodturning practitioners use much more subtle motions against the rotating material, resulting in much finer powder-size grains. The workpiece was composed of 159K elements, and the simulation lasted 9.1 h for 300 frames.

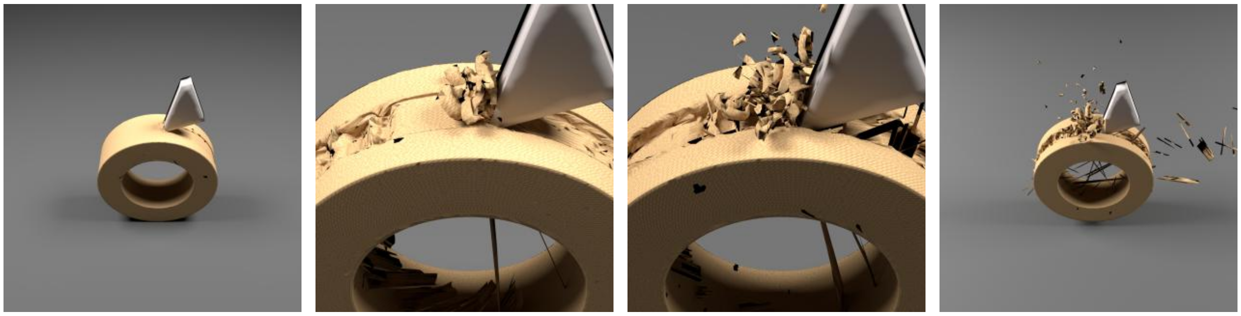


Figure 30. Four instances of a woodturning simulation in temporal order from left to right.

A similar safety issue is encountered in wood cutting, in this case, related to moisture levels in the workpiece. Wet wood absorbs more energy and reduces the risk of splintering. Dry wood can shatter, sending pieces of wood into the workspace at high speed. Safety measures such as securing the wood or using a different technique to achieve the same goal, such as sawing in this case, are typically considered. The cutting of a wooden ply is considered for two conditions, one for a dry and one for a wet wooden ply. In both cases, a metallic wedge follows the same motion during the same 1 s interval. Aside from workpiece humidity, all material properties are the same in both conditions. In Figure 31. Splitting of a wooden ply. From left to right, the first three images are visualisations of the first, middle, and last frames of cutting a wet ply. The rightmost image shows the outcome of the same action on a dry ply., the three leftmost images show three consecutive moments for the first condition. The rightmost image shows the outcome of the second condition. The simulations confirm that using wet wood fosters safer cutting as opposed to dry wood, in which the two pieces bounce on the ground plane and are projected into the workspace. Dry wood material properties were the same as above. For wet wood, density was increased by 15%, while the elastic modulus and Poisson ratio were reduced by 30%. The workpiece was composed of 64K elements, and the two simulations lasted 5.9 h, on average, for 100 frames.

In contrast to wood, metal deforms without creating splinters due to its higher strength and plasticity. In Figure 32. Incision of a golden workpiece. From left to right, the first three images are renderings of the action in the first, middle, and last frames, respectively. The rightmost image renders mechanical stress for each finite element at the end of the action., an incision on a golden workpiece by a rigid tool is simulated. This technique is used in metal engraving, where metal shavings are collected, melted, and reused. It is observed that the material carved away is less than the volume of the cut. As in the FEM simulator, the workpiece is compressed instead of carved out. In the illustration, the rightmost figure visualises the prediction of mechanical stress for each finite element, with lighter colours corresponding to low stress and bright colours to higher stress. Gold density is 19,320 kg/m3. Gold exhibits both elastic and plastic properties. It has a Young's modulus of 76 GPa and a Poisson's ratio of 0.415. The yield stress of gold is 205MPa, and its plastic strain is 0.05. The workpiece was composed of 742K elements, and the simulation lasted 1.7 h for 20 frames.

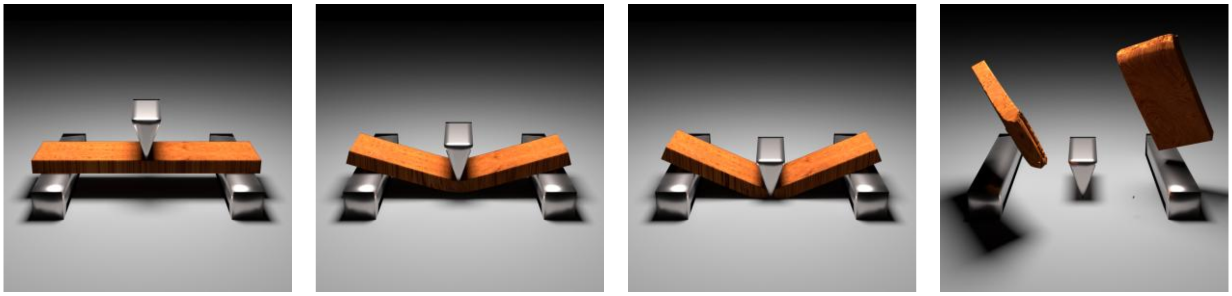


Figure 31. Splitting of a wooden ply. From left to right, the first three images are visualisations of the first, middle, and last frames of cutting a wet ply. The rightmost image shows the outcome of the same action on a dry ply.

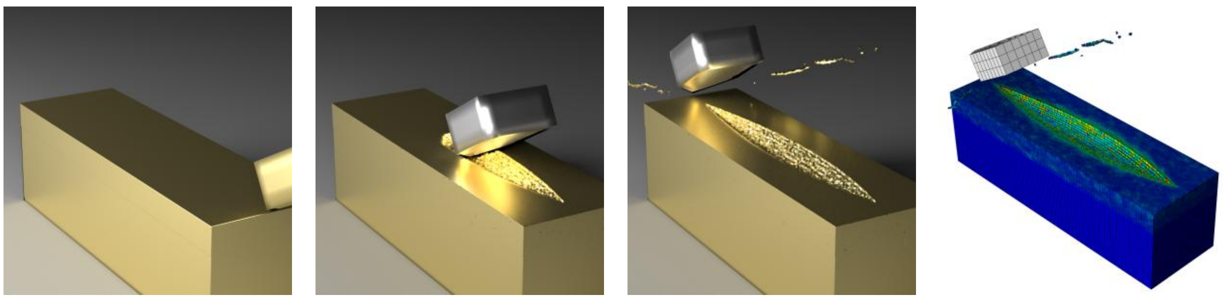


Figure 32. Incision of a golden workpiece. From left to right, the first three images are renderings of the action in the first, middle, and last frames, respectively. The rightmost image renders mechanical stress for each finite element at the end of the action.

Despite the high malleability of metals, larger pieces of material are extracted when an appropriately shaped tool is employed. The edge of a drill has the shape of a thin and twisted wedge. In Figure 33. Drilling a rough copper workpiece with an iron tool. The four renderings are in temporal order from left to right., this is exemplified by simulating the drilling of a copper workpiece by a rigid tungsten drill. In this case, the coarse "railing" of the drill and its propulsion against the workpiece produces greater pieces of swarf. Copper has a density of 8930 kg/m3. Its elastic properties are characterised by Young's modulus of 110 GPa and a Poisson's ratio of 0.343. The yield stress of copper is 150MPa, with an associated plastic strain of 0.02. The workpiece was composed of 312K elements, and the simulation lasted 8.2 h for 200 frames.

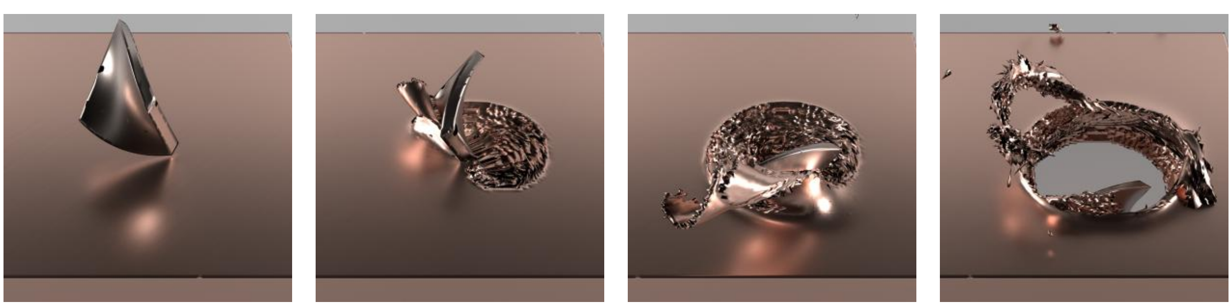


Figure 33. Drilling a rough copper workpiece with an iron tool. The four renderings are in temporal order from left to right.

In Figure 34. Two conditions of a wood carving, one per row and in temporal order, from left to right. In the bottom row, the chisel is pushed harder into the workpiece, leaving a deeper trace., a wood carving action is simulated, in which a chisel is used to carve a wooden workpiece. Wood parameters are the same as above. Two conditions are simulated, in which the modulation of force orientation as a function of time is the same. The two conditions differ in the magnitude of the force applied to the chisel. In the first condition (top), the force is weaker than the second (bottom), resulting in a shallower carving of the workpiece. Using the approach in Section 4.4, this visualisation is performed in real-time for the development of online training. However, as this approach is limited to memory capacity, we can create real-time photorealistic simulations of only simple actions like the demonstrated one. A second carve of the material would require a new pre-computation of the visual results upon the result for the first one. The workpiece was composed of 40K elements, and the simulation lasted 9 min for 20 frames.

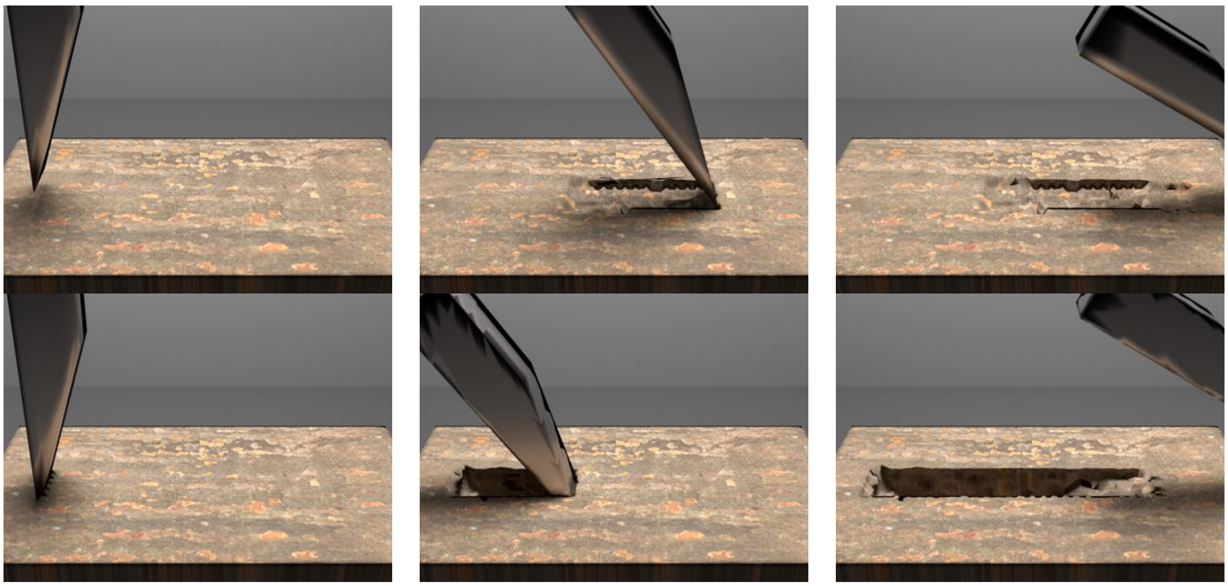


Figure 34. Two conditions of a wood carving, one per row and in temporal order, from left to right. In the bottom row, the chisel is pushed harder into the workpiece, leaving a deeper trace.

8.2 Shaping

Many shaping actions require the use of heat or moisture to permanently deform materials without damaging them. In Figure 35. Bending of a wet wooden ply in temporal order from left to right., the bending of a wooden ply is simulated, indicating the use of moisture. The parameters of wood are the same as for wet wood in the example of Figure 29. Carving a wooden block with an iron wedge.. Higher moisture levels reduce the brittleness of wood as its fibres become more flexible, enabling the wood to bend more easily without cracking or breaking [63]. The flexibility introduced by moisture is temporary; however, proper drying techniques are crucial to ensure that the bent ply retains its desired form after the bending process [64]. The main difference between this experiment with that of Figure 31. Splitting of a wooden ply. From left to right, the first three images are visualisations of the first, middle, and last frames of cutting a wet ply. The rightmost image shows the outcome of the same action on a dry ply. is the shape of the tool. The simulation accounts for the blunt shape of the tool, which results in a less concentrated application of stress on the workpiece, resulting in deformation instead of damage. The workpiece was composed of 10K elements, and the simulation lasted 3.1 min for 27 frames.

Glass becomes softer and more deformable when heated at ≈600–800 °C). At these temperatures, its viscosity decreases, and glass transitions into a malleable state, enabling shaping and twisting without breaking. The density of glass is 2500 kg/m3. In the simulation, the temperature of the glass workpiece is 600 °C. At this temperature, glass exhibits Young's modulus of 30 GPa and yield stress of 5MPa, while, at room temperature, these are 65 GPa and 100MPa, respectively. The reduction in these properties at higher temperatures makes the glass more malleable.

Twisting glass is integral in glassworking techniques such as cane work and is performed at temperatures where glass is malleable but not molten. In Figure 36. Instances of the twisting of a hot glass ply until it folds in temporal order from left to right., the twisting of a green-tainted ply of glass is simulated. The twisting rotates the workpiece from its two edges and about its dominant axis, which, in the figure, is horizontal. The workpiece is continuously twisted until it starts to fold. The leftmost image of the figure zooms at the centre of the workpiece, at its initial state. The remaining images show its state after twisting each of its edges by one, two, and four full circles from left to right. This simulation cannot be performed using the PBSs as deformation and damage would need to be combined. In multiphysics simulators, this operation is transparently handled since both phenomena and their appropriate material properties are enabled. The workpiece was composed of 3K elements, and the simulation lasted 2.1 min for 41 frames.

Figure 35. Bending of a wet wooden ply in temporal order from left to right.

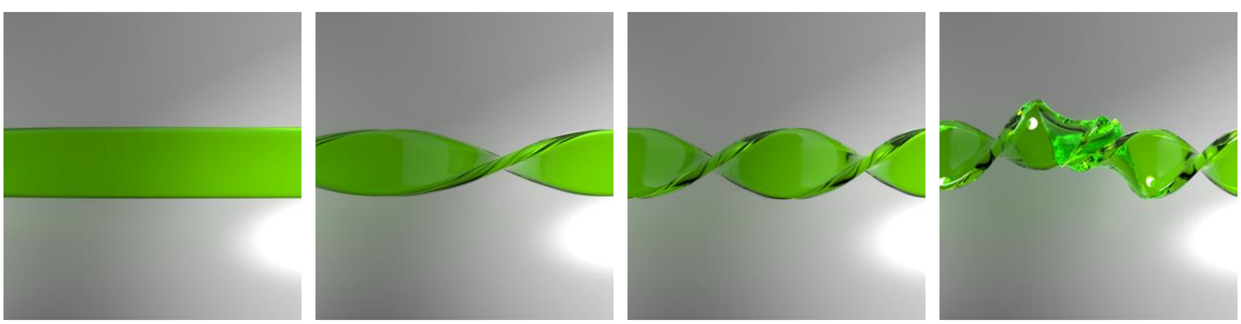


Figure 36. Instances of the twisting of a hot glass ply until it folds in temporal order from left to right.

Heat affects the mechanical properties of metals. As temperature rises, their ductility increases and their yield strength reduces [65]. This makes deformation easier, enabling large reductions in thickness and significant deformations without cracking or breaking. In hot-rolling, heated metals are rolled into thin sheets without the risk of cracks, which are more likely at lower temperatures. The process is simulated for two consecutive steps that gradually reduce the thickness of a copper sheet, as indicated in Figure 37. Hot-rolling of a copper workpiece by two steel rollers in two steps. The first step is shown at the top and the second in the bottom row.. The workpiece temperature is 600 ◦C. At this temperature, Young's modulus is 85 GPa and the yield stress 40MPa. The workpiece was composed of 24K elements, and the simulation lasted 16.2 min for 200 frames.

8.3 Additive

Additive actions may combine two or more workpieces in a way that the identity of each piece is retained, such as in spinning two threads together or fusing them in a whole object, like adding molten glass to a gob.

Glassblowers gather molten glass onto the end of a blowpipe from a furnace using the reflection of the blowpipe in the molten glass as a guide. During "gathering", the practitioner aligns the blowpipe, monitoring its reflection on the surface of the molten glass. The reflection acts like a mirror, helping the glassblower to see if the blowpipe is dipping at an angle, which could result in gathering an uneven or excessive amount of glass. Moreover, refraction cues provide information regarding the depth at which the blowpipe is submerged in the molten glass. In Figure 38. A blowpipe slightly dipped in molten glass. The left and middle images show how a slight displacement of the blowpipe is reflected on the surface of the molten glass. The right image shows the scene in the middle image from a lateral viewpoint., this action is simulated and rendered. The left and right images render the practitioner's view of a correctly aligned and slightly misaligned blowpipe, respectively. The image on the right shows the scene from a lateral viewpoint, demonstrating the simulation of refraction when the blowpipe is submerged in the molten glass. The simulated temperature of the molten glass is 800 ◦C. At this temperature, Young's modulus of glass is 10 GPa, and its yield stress is 1MPa. In this case, only individual poses were simulated; thus, the FEM computation lasted a few tens of seconds.

Figure 37. Hot-rolling of a copper workpiece by two steel rollers in two steps. The first step is shown at the top and the second in the bottom row.

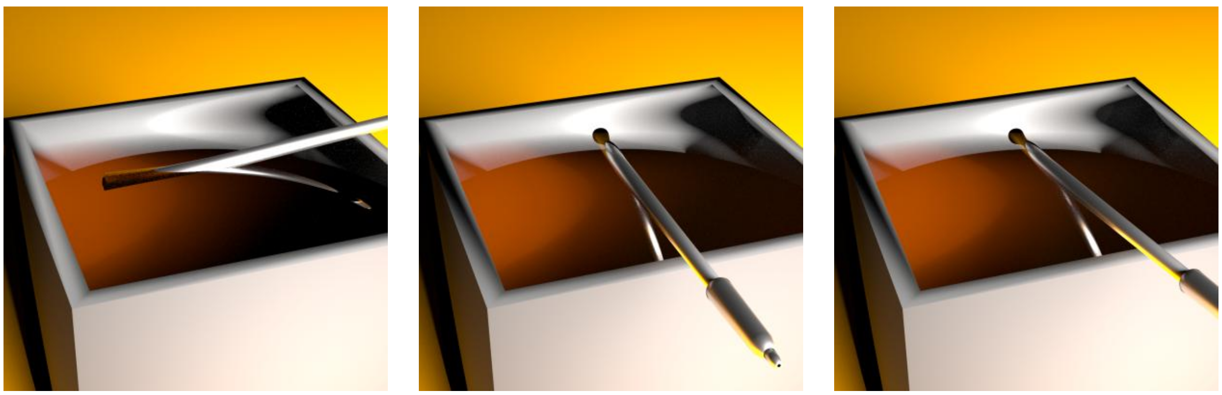


Figure 38. A blowpipe slightly dipped in molten glass. The left and middle images show how a slight displacement of the blowpipe is reflected on the surface of the molten glass. The right image shows the scene in the middle image from a lateral viewpoint.

In Figure 39. Two conditions of driving a nail into a wooden workpiece, rendered in two image pairs. The left pair shows a perpendicular drive, while the right one the driving of a slanted nail., the driving of a nail into a piece of wood is simulated and visualised in close magnification. Two conditions are simulated in which the magnitude and duration of the force driving the nail are the same. The incidence angle of the nail and its driving force are 0° and 30° in the first and second conditions, respectively. The examples render the simulation's initial state and result showing the minor wood deformation for each condition. The results for the first and second conditions are shown by the left and right couples of images, respectively. This example is sufficiently simple to be available in real-time using the technique in Section 4.4. The properties of wood are as in Section 5.2.1. Iron has a density of 7870 kg/m^3, a Young modulus of 200 GPa, and a Poisson's ratio of 0.291. The yield stress of iron is 150MPa, with an associated plastic strain of 0.01. The workpiece was composed of 12K elements, and the simulation lasted 4.1 min and 4.2 min, respectively, for 200 frames.

In Figure 40. Spinning of two threads into a string., two red and blue translucent polyester threads are spun together, indicating the potential of simulating the fundamental action of textile fabrication, as well as the use of new materials. In addition to plasticity and elasticity, friction plays a central role in the spinning of threads because it keeps the interlocked threads together. The polyester density was 1540 kg/m^3, Young modulus was 7GPa, Poisson's ratio was 0.3, and yield stress 150MPa. A perfectly plastic behaviour is assumed; hence, ductility is 0. The threads are in contact only with other cotton surfaces, and the friction coefficient was 0.5 [66]. Each workpiece was composed of 17K elements, and the simulation lasted 1.1min for 200 frames.

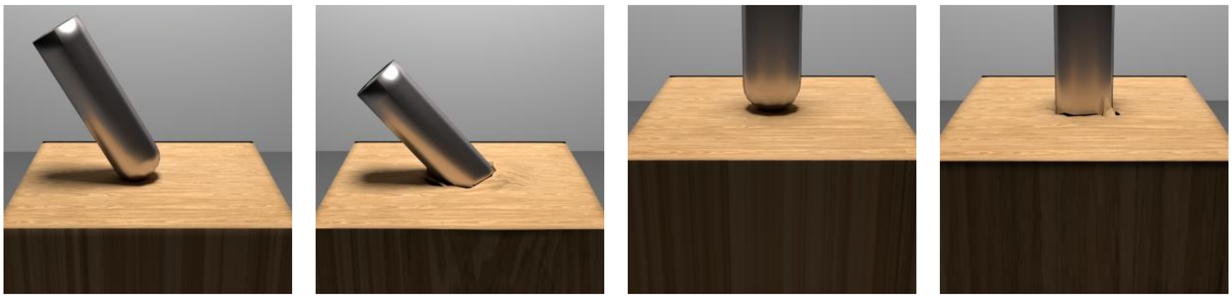


Figure 39. Two conditions of driving a nail into a wooden workpiece, rendered in two image pairs. The left pair shows a perpendicular drive, while the right one the driving of a slanted nail.

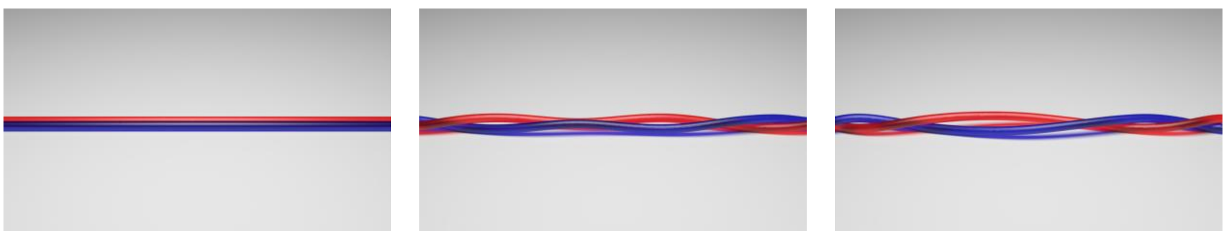


Figure 40. Spinning of two threads into a string.

9 Products

The visualisation toolbox is used to realistically predict the appearance of craft products from their designs or 3D models. This capability serves the product designer to envisage how the prospective creation would look before embarking on its implementation. Moreover, it serves customers in visualising how a given product would appear in the environment in which they are planning to install it. Sustainability is served this way as materials can be expensive and experimentation often requires multiple trials, adding time and costs. Photorealistic simulations enable practitioners to experiment extensively at a low cost, conserving materials and minimising the need for repeated trials. In the examples rendered below, we first use grey background and white illumination to more objectively assess the potential benefits of photorealistic quality. We then use spherical HDRI maps to demonstrate the capacity of visualising products in realistic environments, even when created from shiny, transparent, and translucent materials. The HDRI maps can be captured by conventional 360° cameras. In the examples, these maps are obtained from [67].

In the renderings of this section, the refraction indexes of air and glass are 1.000277 and 1.5046, respectively. Spectrally varying refraction indexes of metals are from [68], and the rough metallic surfaces employ the implementation of [56], both included in the Mitsuba 3 distribution.

9.1 Glazes

Glazing is an important step in the crafting of utilitarian and artistic pottery. The final texture of a pottery piece depends on glaze composition, application thickness, and firing temperature. Visualisations that capture light scattering due to glaze enable the refinement of textures digitally before committing to costly or time-consuming physical trials. Moreover, some glazes contain hazardous materials, requiring cautious handling. Simulating these glazes digitally helps artists to achieve desired aesthetics without using toxic materials in the testing phase, promoting safety and environmental sustainability.

To create the glaze coating, the 3D model is converted into voxels and morphologically dilated. The original model is subtracted, in voxel space, from the "inflated" result of 3D dilation to create a hollow shell that represents the glazing. The surfaces of the two models are combined and rendered. Glazing simulations are shown in Figure 41. Renderings of plates with different glazings. The top row illustrates the differences in appearance of plastic, raw, and glazed clay. The middle row shows the effects of matte and shiny clay on porcelain, and the bottom row shows the effect of tainted glaze use. for three conditions, one for each row.

The top row demonstrates the visual differences between the same two-coloured plates but composed of clay, plastic, and, finally, glazed clay. The first image overviews the glazed clay condition. The next three images show details of the three renderings at a region that features high surface curvature.

The middle row renders a porcelain plate featuring a traditional design. The left image shows the painted porcelain before glazing and firing. The middle image shows the result of a thin and matte glazing. Finally, the right image predicts the appearance when a thick and lustrous glaze coating is applied.

The bottom row demonstrates the effect of tainted glazing. On the left is the rendering on an unglazed clay plate. In the middle, a transparent glaze coats the same plate. On the right, the type and thickness coating is applied, this time tainted with copper oxides, which, when fired, result in a so-called "reduction red" colouring.

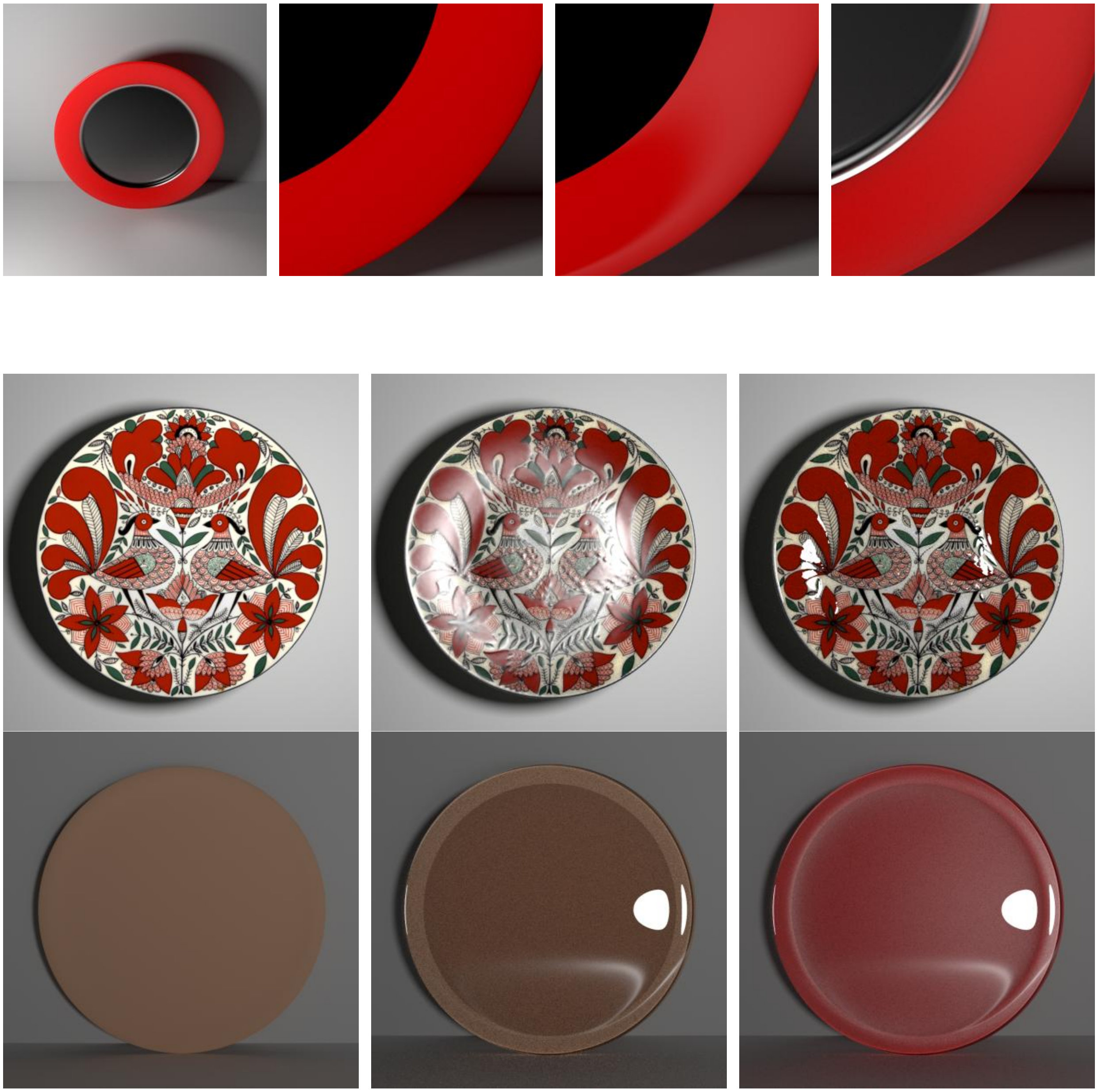


Figure 41. Renderings of plates with different glazings. The top row illustrates the differences in appearance of plastic, raw, and glazed clay. The middle row shows the effects of matte and shiny clay on porcelain, and the bottom row shows the effect of tainted glaze use.

9.2 Metal Engravings

In Figure 42. Engravings on rough metal. Top: designs. Bottom, left to right: copper, gold, and copper predictions of appearance for the corresponding designs in the top row., engraving on metal sheets is shown. The designs are shown in the top row, and the visualisation results are in the bottom. Binary image designs are transferred to 3D surfaces by Gaussian smoothing the design image and interpreting the resultant image intensities as depth on the metallic surface. The left row shows the result for an engraving legend on carving stroke intensity and tooltip thickness, the middle for a vertically oriented design, and the right for a horizontally oriented design, respectively.

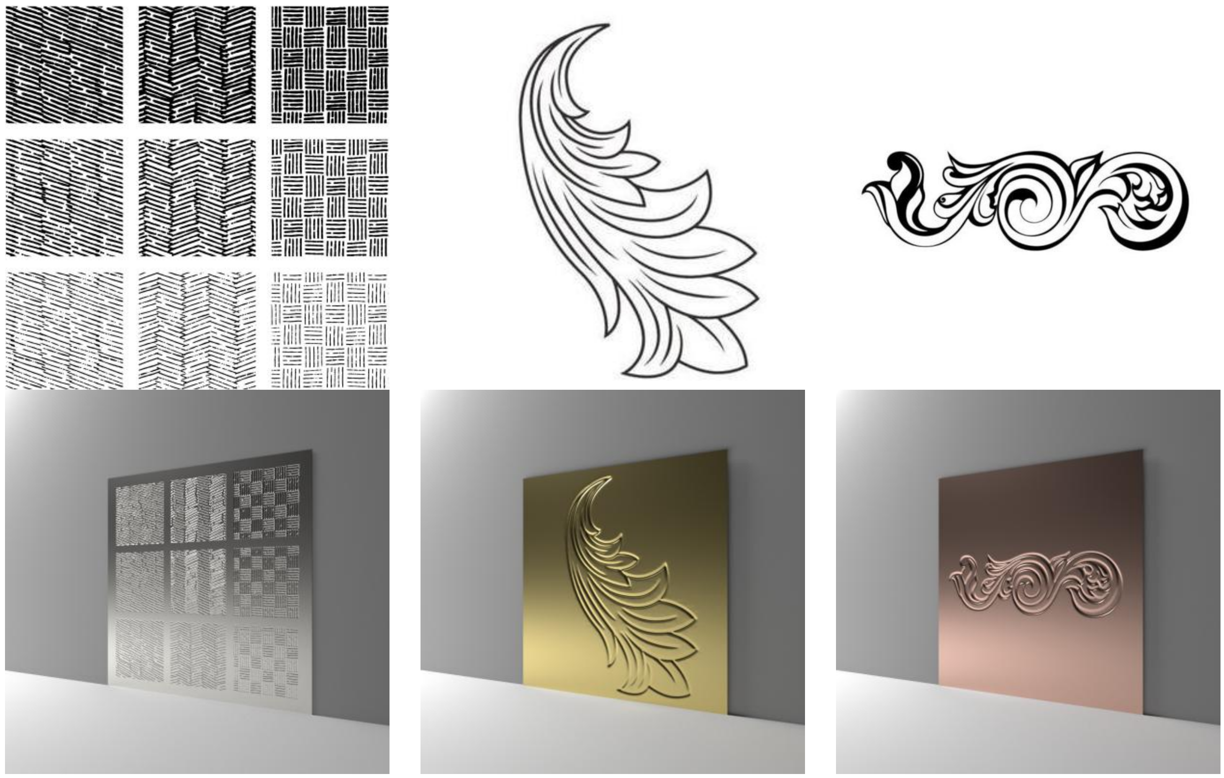


Figure 42. Engravings on rough metal. Top: designs. Bottom, left to right: copper, gold, and copper predictions of appearance for the corresponding designs in the top row.

9.3 Cane Work

In glassworking, cane work refers to a technique involving the use of long, thin rods of glass, called "canes," which are created by stretching molten glass into slender strands. When these canes are then incorporated into the blown piece, they produce decorative effects. In Figure 43. Appearance predictions of cane work compositions., the appearance of cane work artefacts is predicted, created from glass and metal canes. The left and middle images show the same design implemented with different colours of tainted glass. The image on the right shows a composition of glass and metal.

Figure 43. Appearance predictions of cane work compositions.

9.4 Stained Glass

Traditional stained-glass windows used the “came glasswork” process of joining cut pieces of stained glass. Copper foil is a versatile alternative to the traditionally used lead. To facilitate the design of stained-glass windows, a software utility was developed. Given a colour image, this utility creates the 3D models of the parts of a stained-glass composition, that is, the metallic framework and the glass pieces. The algorithm and implementation details for this utility can be found in Appendix A.

In Figure 44. Visualisation of stained-glass compositions. The top row shows a traditional window design (left) and its virtual installation on a stone wall from outdoor (middle) and indoor (right) views. The middle row shows a modern design (left) installed on a grey wall with indoor (middle) and outdoor (right) lighting. The bottom row shows the framework of the model design in detail (left) as well as the window installation with different outdoor environments., this utility is demonstrated. In the top row, a stained-glass window based on a traditional design is shown. In the left and second-from-left images, the stained-glass compositions from the outside and inside of a stone building are shown, respectively. In the indoor case, the illumination of the room and the floor from the coloured light passing through the tainted glass is demonstrated. The image on the right is explanatory and shows how the patterns created by the stained-glass window light can be predicted and customised according to a given configuration. A designer can use these predictions to configure glass colours according to the place of installation.

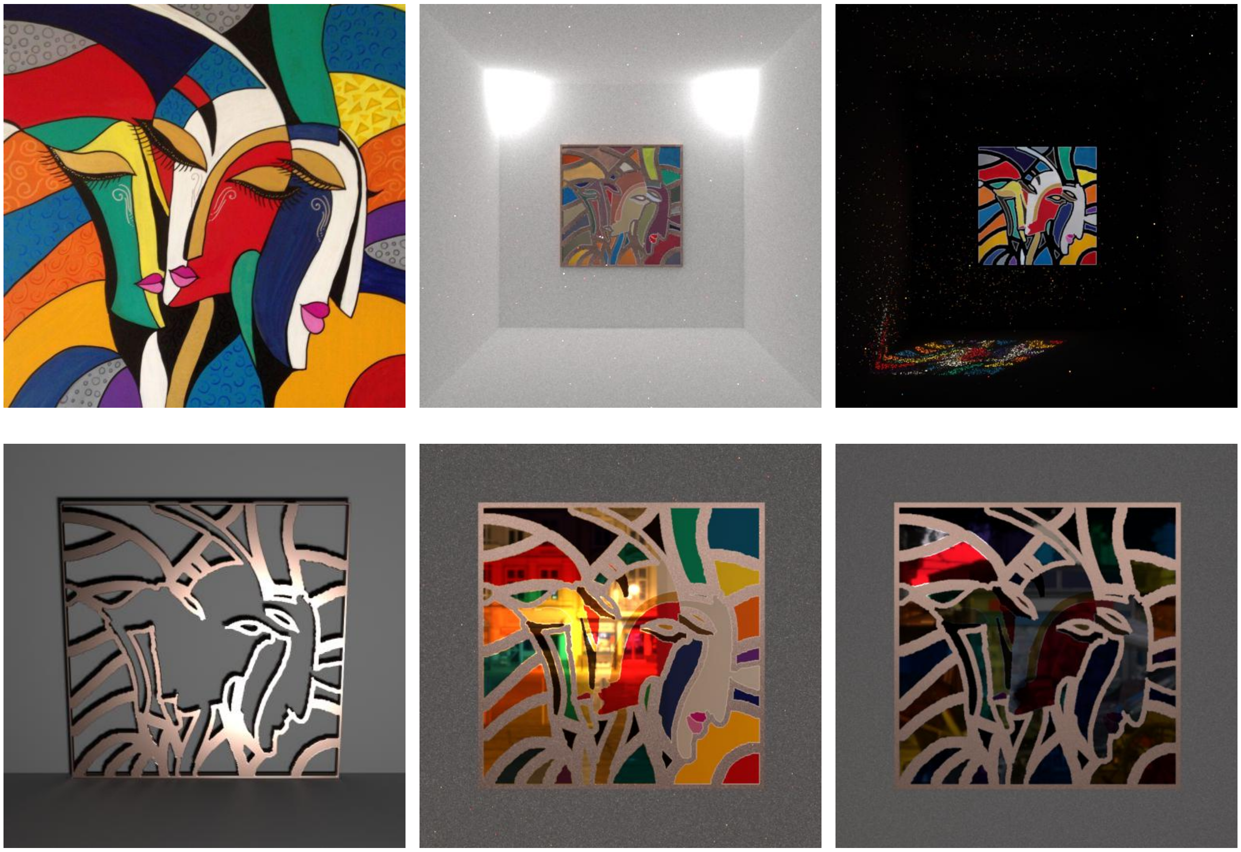


Figure 44. Visualisation of stained-glass compositions. The top row shows a traditional window design (left) and its virtual installation on a stone wall from outdoor (middle) and indoor (right) views. The middle row shows a modern design (left) installed on a grey wall with indoor (middle) and outdoor (right) lighting. The bottom row shows the framework of the model design in detail (left) as well as the window installation with different outdoor environments.

The second example is shown in the middle and bottom rows of Figure 44. Visualisation of stained-glass compositions. The top row shows a traditional window design (left) and its virtual installation on a stone wall from outdoor (middle) and indoor (right) views. The middle row shows a modern design (left) installed on a grey wall with indoor (middle) and outdoor (right) lighting. The bottom row shows the framework of the model design in detail (left) as well as the window installation with different outdoor environments.. A modern design generated from a drawing was used, which is shown in the middle row on the left image. The composition using indoor lighting is shown second from left in the same row. Outdoor lighting is simulated on the right of the middle row, creating colourful projections of light on the floor. In the bottom row, the copper framework is shown on the left. The middle and right images simulate two different environments outside the window, showing that glass transparency enables observation of outdoor structures.

9.5 Tiffany Lamp

The simulation of light sources and transparent materials is employed in the artistic design of indoor lamps. In Figure 45. A Tiffany lamp rendered in neutral (top, left) and other indoor environments (remainder)., the appearance of a Tiffany lamp is simulated in a neutral environment and multiple indoor environments. Next, the environment lighting is simulated using 360 images. To indicate the effect of the lamp on surfaces, two planar surface segments perpendicular to each other have been artificially added to the scene.

Figure 45. A Tiffany lamp rendered in neutral (top, left) and other indoor environments (remainder).

9.6 Solids

The development of solid artefacts, such as sculptures, can be costly depending on the material and method. Stone is carved, while glass and metals are usually moulded. Recently, 3D printing has become a cost-efficient alternative. To support educated material selection, the appearance of solid structures in specific environments can be predicted. This is demonstrated in Figure 46. Appearance predictions of moulded sculptures created from different materials. Left to right: marble, glass, gold, and plastic., where the same sculpture is simulated in the same outdoor environments but created from marble, glass, gold, and plastic filaments used for 3D printing. The original sculpture is created from marble, and its 3D model was obtained from [69].

The appearance of solids depends on the lighting properties and surrounding surfaces in the particular environment because they reflect light according to their composition. In Figure 47. Appearance predictions of marble sculptures in environments with diverse illumination conditions and surroundings., the 3D model of a heritage sculpture [70] is rendered in different outdoor environments. The original sculpture is created from marble and in all the examples is rendered as created from white marble. The examples demonstrate how the light reflected by the surfaces of the environment and the position of the light source affect the appearance of the same geometry and material artefact.

Figure 46. Appearance predictions of moulded sculptures created from different materials. Left to right: marble, glass, gold, and plastic.

Figure 47. Appearance predictions of marble sculptures in environments with diverse illumination conditions and surroundings.

10 User Evaluation

The current state of the software interface for the rendering utility, or visualisation toolbox, reflects the results of a preliminary user evaluation, which provided valuable feedback for initial improvements. The evaluation focused on the usability of the toolbox in developing educational visualisations and craft-specific design applications and documentation. To facilitate this evaluation, a set of use cases were created in the form of exercises, covering the basic functionality of the utility. These exercises were assigned to four junior developers, who completed them and subsequently responded to questionnaires and participated in informal interviews.

The exercises were divided into two subsets. The first subset focused on rendering images and rotational videos of static objects and scenes, as well as animation videos generated from simulations. The evaluation emphasised ease of use, the design of the API, and the overall learning curve for users. The second subset centred on craft-specific functionalities, requiring participants to create a cane work composition, a stained-glass window installation, and a metal engraving. Here, the primary focus was on the documentation—specifically its clarity, completeness, and organisation—assessing how easily developers could create a design example application based on the provided resources.

All developers completed the tasks within 30min. Feedback from the first subset primarily highlighted issues with documentation and the need to clarify certain concepts used as input for the toolbox functions. For example, there was ambiguity between "rotational videos", which present a static object rotating through 360° in the frame, and "animation videos", which display dynamic results from simulations. Additionally, a functional requirement emerged: the ability to rotate the rendered object or scene itself rather than just the virtual camera.

Feedback from the second subset of exercises revealed challenges specific to craft-based tasks. Some developers expressed unfamiliarity with the cane work craft, while others found it difficult to manage the multiple files required for the stained-glass composition. Participants also requested fully pre-configured example files to reduce reliance on the documentation when authoring their configuration files.

A more comprehensive user study focusing on craft-specific applications is planned for future work. Based on the feedback from this evaluation, several improvements were implemented: functionality was enhanced, the documentation was refined and visually illustrated, and craft-specific features were supplemented with illustrated examples. Additionally, example configuration files are now provided to streamline the user experience, and a troubleshooting section was added to the documentation to address common issues encountered by new users. The online version of the toolbox includes these improvements.

11 Discussion

In this section, we discuss how the proposed work stands in the context of technical craft research and how it supports craft sustainability.

11.1 Contributions to the Field

This work advances the state of the art in the digital modelling, visualisation, and preservation of craft practices by scalable, adaptable, and craft-specific orientations required to effectively model, simulate, and visualise craft actions. The proposed framework bridges these gaps through innovations in simulation, rendering, and usability, tailored specifically to the needs of craft-focused applications.

A major contribution of this work is its scalable approach to modelling craft actions using Finite Element Method (FEM) simulations. This framework resolves this limitation by focusing on actions, or “unit activities”, that can be combined to synthesise more complex processes. This scalability enables the framework to represent crafting actions at varying levels of detail depending on the application requirements. As a result, it enables both high-fidelity offline simulations and more lightweight real-time interactions.

To address the aesthetic limitations of the current simulation visualisations, this work integrates PBR techniques into the visualisation pipeline. By enhancing the realism of material appearances and dynamic physical interactions, the framework provides a visual output that is both technically accurate and visually useful. This capability is particularly valuable for craft education, where realistic representations help to convey the intricate details of material behaviour. Furthermore, the framework is adaptable to computational constraints and can be seamlessly integrated with game engines. This ensures that the benefits of high-fidelity rendering are accessible for both offline visualisations and real-time applications. The authoring framework is designed around the modelling of craft actions and their associated physical entities. By embedding the tools, materials, and interactions inherent to crafting into the framework’s design, it provides a platform that aligns closely with the workflows of craft practitioners and educators. This craft-oriented approach supports applications ranging from digital preservation and education to innovative design and prototyping.

A key strength of this framework lies in its usability and adaptability, validated through preliminary user testing with developers. The inclusion of pre-configured examples, detailed documentation, and troubleshooting resources makes the framework accessible to a wide range of users, from software developers to craft practitioners. The feedback from these tests has driven iterative improvements, ensuring that the framework meets practical needs while maintaining flexibility for diverse applications.

11.2 Limitations

The main limitation of this work arises from the high computational complexity of advanced simulation and rendering methods. Although parallelisable, FEM-based simulations are excessively time-consuming for modern hardware to be directly employed in interactive applications. In contrast, real-time simulation methods offer sufficiently accurate approximations for many use cases, but they fall short in addressing specific and more complex scenarios. Similarly, in the realm of visualisation, while real-time rendering performs adequately for static objects and matte materials, achieving photorealism in dynamic phenomena remains a substantial challenge in most general cases.

Another limitation is the focus of this work solely on visual stimuli, whereas craft practitioners rely on multiple sensory inputs during their practice. Audio and haptic stimuli, as well as temperature, play critical roles in many crafts. Practitioners often employ specialised gestures to engage with these stimuli, such as knocking on wood to determine whether it is hollow or touching a surface to assess its smoothness or roughness. In addition, practitioners frequently adapt to environmental stimuli, such as background noise in workshops or heat in glass hot shops, integrating these sensory experiences into their workflow.

In a different vein, the visual stimuli simulated in this work primarily provide explanatory and educational value, which can be further enhanced when paired with verbal content and comprehensive documentation. Consequently, the developed framework would be better utilised if integrated and contextualised within an authoring platform tailored for craft education and training. This would enable more effective dissemination and application in educational contexts.

11.3 Adaptability

The proposed framework aligns the computational requirements with appropriate visualisation approaches. Training applications that necessitate interaction are addressed using real-time methods. Although these simulations rely on approximations to achieve real-time performance, they effectively capture the fundamental principles of mechanical phenomena, making them valuable for craft training and skill development. At present, to interactively simulate advanced phenomena using FEM simulation, individual actions are isolated—such as those depicted in Figure 34. Two conditions of a wood carving, one per row and in temporal order, from left to right. In the bottom row, the chisel is pushed harder into the workpiece, leaving a deeper trace. and Figure 39. Two conditions of driving a nail into a wooden workpiece, rendered in two image pairs. The left pair shows a perpendicular drive, while the right one the driving of a slanted nail.—and all the anticipated simulation outcomes are pre-computed.

Professional-grade product design or artefact conservation scenarios often require higher levels of visual realism. Realistic simulations serve as an educational resource, facilitating the observation of craft techniques and providing “sensory imagery” that is challenging to convey through traditional verbal or static visual media. However, in these scenarios, offline visualisation is acceptable and often the standard, particularly when rapid previews are available. Conversely, realistic visual cues are critical for developing a practitioner’s sensitivity to environmental stimuli—a skill that is essential for tasks that demand acute attention to specific contextual factors. To support these goals in interactive applications, we are exploring future work and advancements in hardware acceleration.

12 Interfacing

Although the utilisation of archetypal simulations in interactive and immersive environments is not part of this deliverable, we must make sure that the archetypal simulators are compatible and can be used in the software that implements these environments. The Unity game engine has been selected as the implementation tool for the virtual environments that will be implemented in Craeft. This section describes the process of implementing the interface between the Simulia Abaqus software into the Unity game engine.

The reasons behind the selection of the Unity game engine as the development platform for interactive, immersive, and 3D applications are the following:

- It supports cross-platform development which enables the creation of applications that can be deployed across multiple platforms with minimal changes to the source code.
- It has a robust community and support due to the large and active community of Unity developers, which is a valuable resource for troubleshooting, sharing, and learning from others' experiences.
- It provides extensive integration capabilities with other software platforms which is important for Craeft since we plan to integrate haptics, VR, and AR with the applications developed in it.
- It is quite cost-efficient and users have to pay for a license only when there is commercial exploitation of products developed with it.

All technical partners of the consortium have significant experience using it.

As mentioned in Section 3.8, we use the surface description of the simulation output to interface with virtual environment engines. As Simulia Abaqus does not offer a file format directly compatible with Unity, we used the exported WRL file format and devised a solution for interfacing with Unity which is outlined below.

To illustrate the process, we use an example of an archetypal simulator where a piece of material is cut with a sharp tool. In this case, we instantiated the simulation for the wood material and the implementation in Unity used an analogous texture. The archetypal simulation is shown in the figure below:

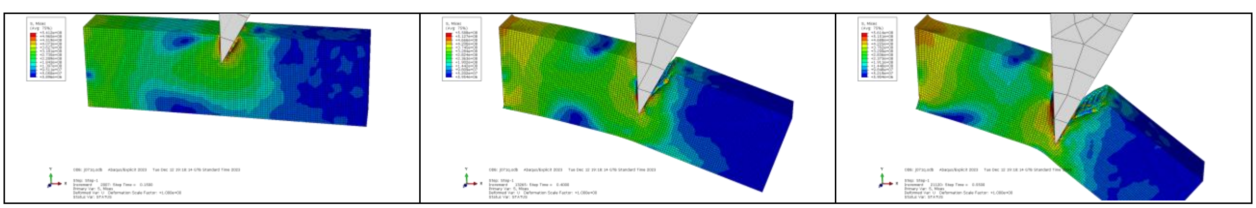


Figure 48. A simulation of cutting a piece of material.

The following procedure was employed to import the simulation output to the Unity game engine.

1. Since the WRL file contains all mesh, material, and animation data in a single file, creating a custom parser to separate these components was necessary. The process begins by dividing the

original WRL files into several files, each representing a single frame of animation. This splitting is guided by the detection of specific markers within the file (see figure below):

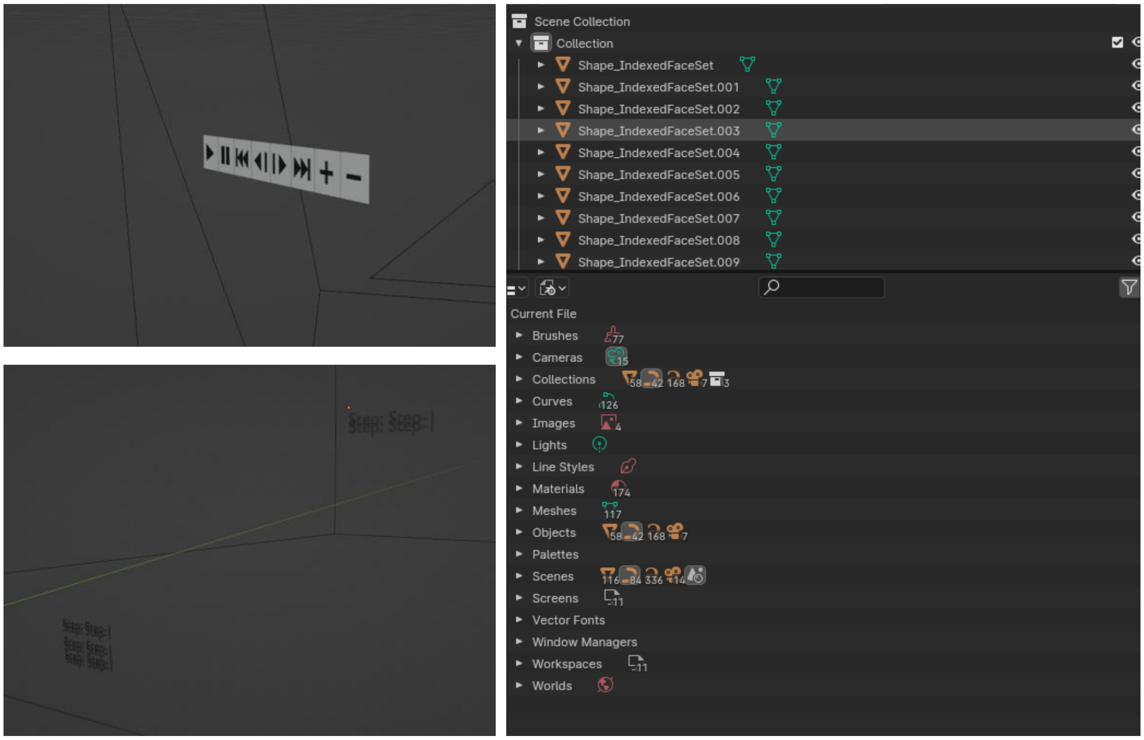


Figure 49. Analysis of input file from Simulia Abaqus and identification of animation frames.

2. **Identifying Animation Frames:** The parser scans for the string "#Drawing the Glyphs". The presence of this string signifies the start of a new animation frame. Upon encountering this string, the parser initiates the creation of a new WRL file dedicated to that specific frame.
3. **Removing Unnecessary Elements:** Since Simulia Abaqus exports all elements in the scene as meshes—including non-essential items like text and UI components like the play button—these extraneous elements need to be filtered out. This clean-up is performed by identifying and acting upon lines containing specific strings within the WRL file. For instance, the line "#Drawing the Glyphs" is a key indicator. When the parser encounters this line, it disregards all subsequent lines from the beginning of the curly bracket '{' to its closing '}'. This selective exclusion is applied across each WRL frame file.

This approach ensures that for each result, the WRL file is streamlined, containing only the essential data for each animation frame, free from surplus mesh, lines, text, and vertices that were originally part of the broader scene exported from Simulia Abaqus.

4. Once the parser completes its task, a .WRL file is generated for each frame, containing only the necessary vertices. However, these files must be converted into a format Unity can recognise and use for animation. This conversion is achieved through a combination of a Python script and a geometry node setup in Blender. The process involves the following steps:

a. **Creating a Foundation in Blender:** An empty mesh is created in Blender. This mesh is then equipped with a Geometry node setup named "ObjToAlembic."
b. **Organising WRL Files:** The Python script searches through a folder structure to locate all WRL files. These files are imported into Blender, with each folder of WRL files from its collection. If there are multiple folders, each with its set of WRL frame files is imported as separate collections.
c. **Pre-processing in Blender:** As the .WRL files are imported as 3D meshes into Blender, they undergo a "cleaning" process. This cleaning includes the removal of loose vertices, the elimination of overlapping vertices, and the standardisation of normals for consistency.

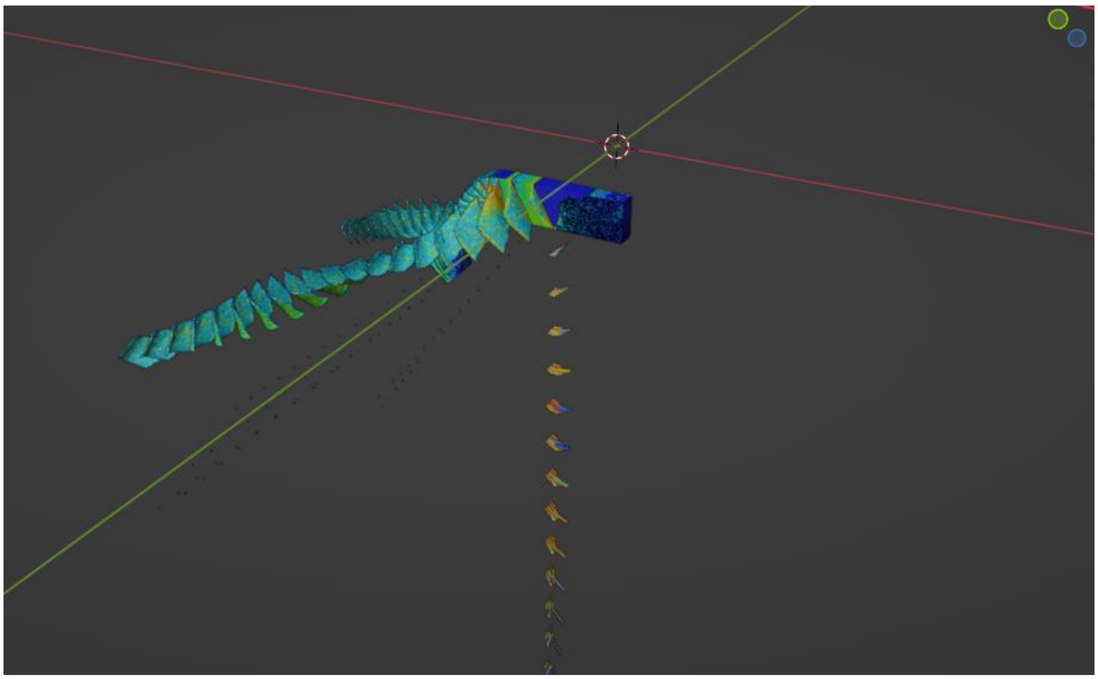


Figure 50. Animating and exporting 3D video frames in Blender.

d. Animating and Exporting: Each Blender collection corresponds to a set of WRL files are attached to the "ObjToAlembic" geometry node setup. This setup is designed to place each mesh sequentially along the timeline, effectively creating an animation sequence. This sequence is then exported as an Alembic (.abc) file, a format compatible with various game engines, including Unity.

Through this method, the original WRL files from Simulia Abaqus are transformed into an animation-friendly format, enabling their use in Unity for dynamic and interactive visualisations. The combination of Python scripting and Blender's geometry node capabilities streamlines this conversion process, ensuring efficient and effective preparation of 3D animation data.

5. The final step involves importing the Alembic file into Unity and configuring it for playback. It is important to note that Alembic files are run from the disk in Unity. This means that animations with denser meshes require a faster SSD, as Alembic essentially displays a new mesh for each frame. This requirement underscores the importance of thoroughly cleaning and optimising the file beforehand to ensure smooth playback.

In the figure below the rendering of the simulation in a video in Blender is shown. The full video can be found on the Craeft YouTube channel: https://www.youtube.com/watch?v=3godXrVrEfY

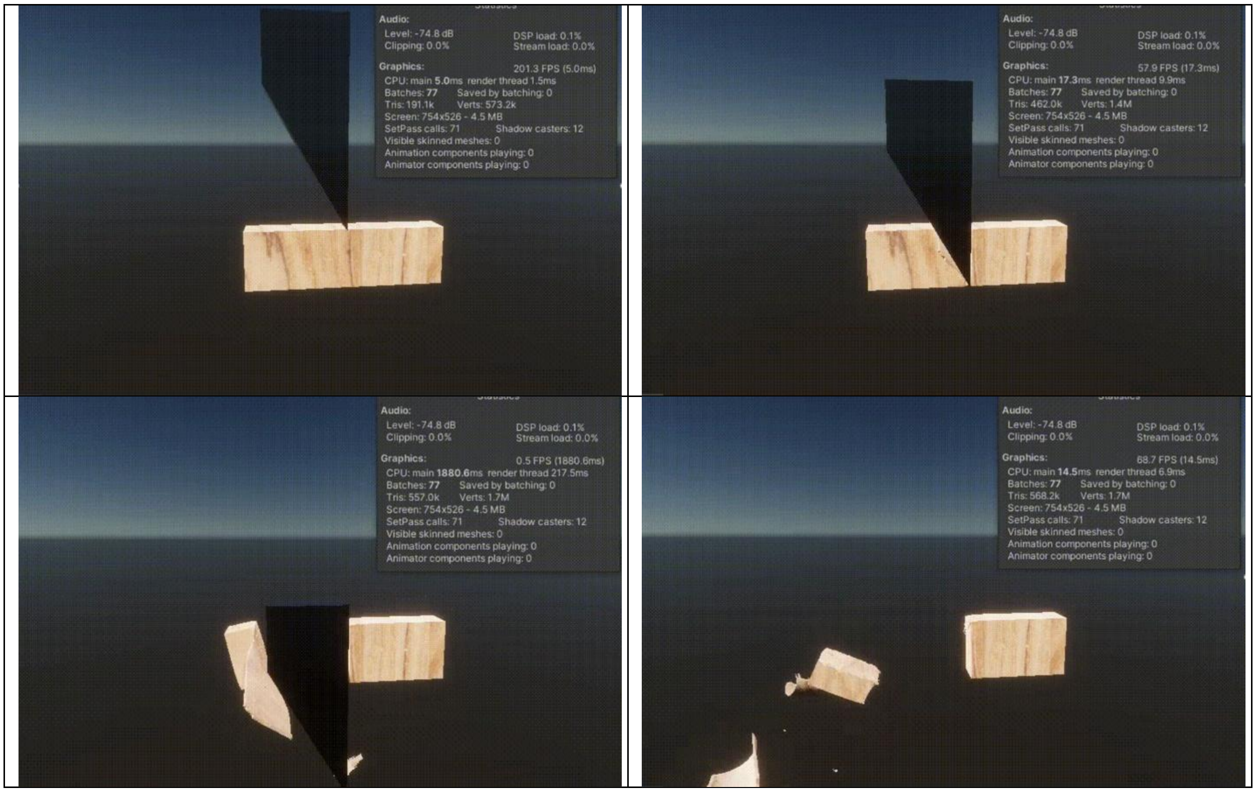


Figure 51. Final alembic animation result in Unity with a tri-planar material added to the wood.

13 Conclusions

This deliverable begins with an introduction in Section 1, outlining its purpose, scope, and the definitions of key concepts. Section 2 comprehensively reviews the current state of crafting simulation, covering theoretical models, simple craft simulators, craft presentation systems, visual simulations, the use of the Finite Element Method for mechanical simulations, textile modelling software, and robotic re-enactments of crafting actions. Section 3 details the project's approach to modelling crafting actions and affordances, including environmental conditions, material properties, object shapes, and causing entities, and classifies actions into additive, subtractive, interlocking, and shaping categories. Section 4 connects these findings to the Maker Material Negotiation model, defining the ontology of action classes and presenting an action description template. Section 5 discusses the technical simulation approach using the Finite Elements Method and its integration with the Unity engine for crafting training applications, the design of simulation archetypes, and the testing of these simulations, with results stored on the Zenodo platform. Section 6 explains how the simulations can be exported to virtual environments, specifically using the Unity game engine.

The next steps of this work are classified into two lines of work.

The first line of work is to complete the archetypal simulators in Section 5 with subclasses of actions that we might have missed and discovered through further analysis of ethnographic studies. Furthermore, we will create multiple instances of the subclasses for the different shapes of tools and materials used in the ethnographic studies. For this purpose, we need to implement a way to directly import 3D models of tools, obtained either from the digitisation of CAD models, in the simulations.

The second line of work is to implement a way to automatically export variants of these simulators for different action parameters, such as the incidence angle of a cutting tool or its force. Our approach will be based on the open format of the simulation input files. Specifically, we plan to write software that systematically modulates the execution parameters of the simulation and collects the simulation results. In turn, these results will be used to create all possible outcomes of each action so that we can create interactive simulations. Although these could be used to create a “lookup table” of possible outcomes that is used for different parameters it will probably require a large storage capacity. Therefore, we plan to use neural networks to learn these outcomes and provide real-time interactivity.

13.1 Safeguarding and Sustainability

ICH preservation goes beyond the mere conservation of recordings as “frozen in time”, requiring skill and knowledge transmission [71], which are prerequisites for the continuation of practice [72]. Interactive media aid vocational training in tasks requiring the interpretation of environmental stimuli during physical actions. The realistic visualisation of stimuli is important because humans “educate [their] attention” [73] to detect environmental stimuli that signify the state of materials and the progress of the task at hand, such as in the simulation of visual stimuli in Figure 38. A blowpipe slightly dipped in molten glass. The left and middle images show how a slight displacement of the blowpipe is reflected on the surface of the molten glass. The right image shows the scene in the middle image from a lateral viewpoint..

Interactive simulation supports virtual practice, contributing to safety training while conserving the energy and materials typically used during the parts of the training process. Additionally, interactive simulation facilitates distance tutoring, enabling practitioners to diversify their income sources and reduce transportation needs, thereby connecting with a broader audience. In this respect, training simulations such as those in Figure 26. Real-time and offline renderings of clay throwing.-Figure 28. Renderings of three moments of a woodturning activity using a steel gouge in temporal order from left to right. are performed with less realistic quality to be interactive as the benefit is still significant.

Design simulations, such as several of those presented in Section 5.3, foster innovation by enabling practitioners to explore new materials and techniques, assessing their potential usability and effectiveness before implementing them in real-world applications. Meanwhile, product previews and visualisations play a pivotal role in public engagement by conveying the aesthetic qualities of crafts and fostering an understanding and appreciation of their cultural significance. These visualisations highlight the care, judgement, and skill involved in the work of individual practitioners. This awareness is especially valuable for endangered or lesser-known crafts, where preservation efforts and broader recognition rely on an authentic presentation of their aesthetic and cultural essence.

13.2 Future Work

This work aligns with the anticipated advancements in computational hardware, particularly in graphics card technology. The integration of additional sensory modalities enhances realism, which, in turn, improves both the memorability and didactic effectiveness of training applications. The expected increases in computational capacity hold the potential to extend these methods to incorporate haptic and audio rendering.

Recent advances in view synthesis methods present promising potential for enhancing real-time approximations of physically based rendering techniques. These advancements could bridge the gap between computational efficiency and visual realism, facilitating more accurate real-time visualisations. The next technical developments in this area are centred on training Neural Radiance Fields [51] and Gaussian splatting [74] for specific craft actions; in this context, [75] used Gaussian splatting to improve the rendering results from dynamic scene reconstructions.

Audio stimuli play a critical role not only in ensuring workshop safety but also in facilitating precise action control and material quality assessment. For instance, sounds such as scraping or sanding can reveal surface smoothness or texture, cracking noises can signal material failure, and resonance from tapping can provide feedback regarding a material’s density or the presence of hollow sections.

Haptic stimuli are equally vital for understanding interactions and materials. Through haptic feedback, trainees can perceive the forces involved in tasks like cutting, drilling, or gripping, enabling improved precision and reducing errors. Beyond tool operation, haptic sensations such as surface texture, temperature, and pliability are essential in contexts where fine motor control and sensitivity are required. By simulating these tactile experiences, haptic rendering significantly enhances the depth and realism of training, fostering both skill development and an intuitive understanding of the materials and tools.

Appendix A. Stained-Glass Window Design Utility

This utility takes as input an image and interprets it as a “came” glasswork composition. Its output includes the 3D models of the glass pieces and the metallic framework, or “came”, needed for its assembly. The motivation is to interpret designs that are easily encoded in digital drawings, but any type of image can be used as input. The image is segmented into connected regions of approximately the same colour. The colour segmentation in Ref. [76] is employed, but any other can be used. The segmented regions are interpreted as glass pieces that are to be mounted on the came. The utility

produces the data structures for the 3D models of the came and glass piece and encodes them in individual files in OBJ format. A configuration file that describes the scene for the visualisation toolbox of Section 4 is also produced. Technical details that enable the reproduction of this utility are provided below.

Appendix A.1 Glass Pieces

The segmented regions entirely cover the image space. To secure space between them for the came, an “open” and a “closed” morphologic operation are applied. Opening and closing are operations that modify the shapes in binary images and are based on erosion and dilation morphological operations. Opening is performed by first applying erosion, which removes small objects or noise by shrinking image regions, followed by dilation to restore the primary structure of larger objects. Closing, conversely, starts with dilation, which fills small gaps or holes by expanding image regions and is followed by erosion to preserve the original object size [77]. The structuring elements in both of our operations are disks. The diameters of these disks on each operation are user-defined, and their values determine the width of the came. The result is a binary image M that has disconnected image regions as foreground. The background is assumed to be the came.

Each region represents a piece of glass and is extruded into a 3D model. The thicknesses of the glass and the came are user-defined. A 3D mesh of triangles is generated for each piece as follows:

1. Triangulate the image region using the Delaunay method [78].
2. Trace the contour boundary points of the region using [79].
3. Convert the 2D region points into 3D points by adding zero (0) as their Z-coordinate.
4. Replicate the 3D points of step #3 and assign them as Z-coordinates regarding the
5. thickness of the stained glass.
6. Replicate the triangles found in step #2 for the new points generated in step #4.
7. Identify the 3D boundary points of the point sets, produced in steps #3 and #4, using
8. the 2D points from step #2 as pivots.
9. Create boundary triangles, following the 3D boundary points from step #6, creating
10. two triangles for a pair of consecutive boundary points.

Appendix A.2 Metallic Framework

Image M is first "padded" by δ rows and columns to create the outer rectangular frame of the came. To create its 3D model, we visit all points $\mathbf{p} = (p_x, p_y)$ in M except those in the last row or column. We consider a 2×2 neighbourhood H with its top-left point at coordinates (p_x, p_y). Let $(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3, \mathbf{p}_4)$ represent the points in H and n the number of black pixels in H. Then,

- if n = 4, we define 2 triangles, $(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)$ and $(\mathbf{p}_3, \mathbf{p}_4, \mathbf{p}_1)$;
- if n = 3, we define 1 triangle, connecting the 3 black pixels in H.

Case 1 and the four possible subcases of case 2 are illustrated in Figure 52. The five principles of triangle formation as occupancy cases in the 2×2 neighbourhood H., with the triangle(s) defined as triangles superimposed.

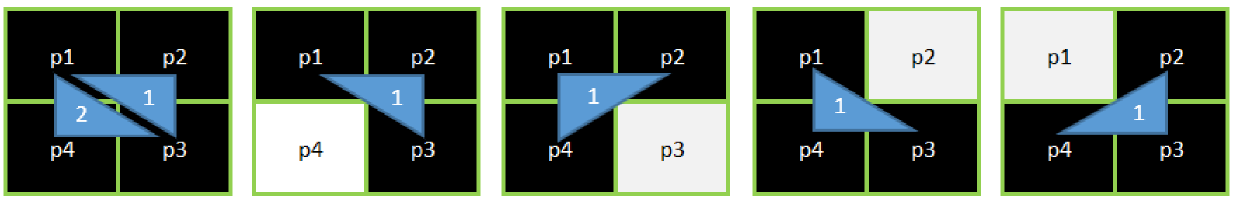


Figure 52. The five principles of triangle formation as occupancy cases in the 2×2 neighbourhood H.

In the same way, as for the glass pieces, we extrude the 2D shape, duplicating the triangles for the "upper" and "bottom" faces of the came; that is, one triangle has Z = 0 and the other has Z equal to the thickness parameter.

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