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Modelling and Simulation of Traditional Craft Actions

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Abstract: The problem of modelling and simulating traditional crafting actions is addressed, motivated by the goals of craft understanding, documentation, and training. First, the physical entities involved in crafting actions are identified, physically, and semantically characterised, including causing entities, conditions, properties, and objects, as well as the space and time in which they occur. Actions are semantically classified into a taxonomy of four classes according to their goals, which are shown to exhibit similarities in their operation principles and utilised tools. This classification is employed to simplify the create archetypal simulators, based on the Finite Element Method, by developing archetypal simulators for each class and specialising them in craft-specific actions. The approach is validated by specialising the proposed archetypes into indicative craft actions and predicting their results in simulation. The simulated actions are rendered in 3D to create visual demonstrations and can be integrated into game engines for training applications.

Keywords: traditional crafts; finite elements; action simulation

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1. Introduction

Traditional crafting is a significant aspect of human activity and a form of Intangible Cultural Heritage (ICH) [1]. Unlike other forms of ICH, such as music, theatre, and dance, the digitisation and systematic documentation of traditional crafts have been relatively left behind. This delay is attributed to the complex and multifaceted nature of capturing the tangible and intangible dimensions inherent in traditional crafts [2] and the uncertain outcome of crafting actions, or the "work of risk" Pye [3], that describe the "negotiation" the maker, and the material [4].

Recent efforts to streamline the recording and documentation of crafting processes focus on representing human motion, tool, and artefact shapes and identifying individual actions through video and motion capture recordings [5]. The outcome of these efforts is a representation that visually and semantically documents craft processes, adhering to international standards for cultural heritage documentation [6]. The achieved representation ostensively indicates the descriptions and audiovisual recordings associated with actions.

The gap that this work aspires to reduce is the association of semantic and audiovisual descriptions with the physical and mechanical phenomena that explain them, which is crucial for its understanding and transmission to new apprentices. To bridge this gap, we turn to generative models particularly physical simulation, to ensure the validity of simulated models. Given the diversity of physical aspects and interactions in crafting actions, we adopt the Finite Element Method (FEM), to address the separate physical disciplines required.

This work builds upon existing representations by integrating mechanical models that are generative, meaning they can be computationally executed to simulate crafting actions and produce representations of their predicted outcomes as material transformation phenomena. Traditional crafting processes involve multiple physical entities and interactions. To facilitate analytical study, we isolate the fundamental elements of crafting activities, which are the individual crafting actions, or "the unit activity attended by a practitioner" [7]. To address the diversity in the mechanics of crafting actions, we propose a classification system that groups actions sharing similar mechanical characteristics, allowing them to be simulated in analogous ways. Through this approach, "archetypal" action models, or "templates" are developed for these categories and then tailored for specific actions and materials.

The proposed contribution includes the identification of physical entities for each action type, the archetypal models for each action, and the computational approaches to implementing simulations for each class, based on the material and action involved. The simulation results can be a computer for multiple ways of executing actions and observing their results, providing a basis for interactive, training applications that economise craft training and increase its safety.

The scope of this study does not encompass all existing mechanical models and materials but prioritises those most relevant to traditional crafts. Moreover, it considers general material types commonly used in traditional crafts—such as metal, fibre, and wood—and relies on indicative material property constants from the literature and established online resources. However, accurate simulation requires the properties of the specific material or behavioural model used, which may necessitate extensive calibration for uncharacterised materials (e.g., an indigenous type of timber). As such, this work serves as a framework where the proposed models and properties can be refined as more specific or new knowledge becomes available.

In Section 2, we conducted a literature review to position the proposed work within the context of the existing research. Section 3 introduces the theory of our approach, which is the identification of physical entities relevant to the representation of crafting actions and their classification into four fundamental categories that simplify their simulation. In Section 4, we utilise this classification to develop FEM simulation templates that can be specialised to facilitate the simulation of crafting actions across tools, materials, and practitioner motions. In Section 5, we test and demonstrate the specialisation of these templates to representative actions from each identified category to demonstrate the effectiveness of the proposed FEM-based modelling and simulation approach. Conclusions and future directions are provided in Section 6.

2. Related Work

Works relevant to the presentation, understanding, modelling, and computational simulation of actions in traditional crafts are reviewed.

2.1. Presentation

Recent trends in the presentation of traditional crafts employ immersive techniques to facilitate comprehension and place the presented information and knowledge in a spatial context with the workshop, serving as the documentation and demonstration of traditional techniques.

In [8], a mobile Augmented Reality (AR) system that superimposes 3D craft objects in space is proposed. The system triggers the virtual demonstration of their usage using a multi-touch surface. In [9], a Head Mounted Display is used to present traditional craft objects with high presence and absorption. In [10], an AR system augments a given physical object with audio and visual digital assets, relevant to its making. A user study is conducted to bring insight into methods of combining virtual and physical materials, to present a narrative located in the decoration of the object.

Virtual Reality (VR) and handheld controllers are used for more realistic virtual handling and interaction with the presented 3D craft objects. In [11], VR demonstrations for two crafts are provided for the production of two Greek traditional alcoholic beverages.

The demonstrations employ pre-recorded interactions with tools and machines, which in VR can be viewed from any viewpoint. In [12], visitors are immersed in a VR environment where they can perform some indicative woodworking tasks, in the context of introducing the usage of dovetailing carpentry tools. The simulation of potential interactions is pre-recorded and shown as animations.

2.2. Robotic Re-Enactment

Automated manufacturing of crafting products was initiated in the Industrial Revolution and textile manufacturing. Today, robotic automation is the norm in manufacturing industries [13] for precisely predefined tasks. In this subsection, work that attends to the recreation of human crafting motion is reviewed.

Mimicking human freehand motion using robots has been mainly studied for carving tasks. As robotic motion has fewer and different degrees of freedom than humans, for a robot to achieve the same tool movement as a human, it is required to convert human kinematics for the available robotic embodiment. In [14], human movements are analysed into their principal components and then encoded to robot kinematic instructions. In [15–17], these components were approximated through machine learning.

Taking an inverse approach, other studies focused on achieving the same result as human actions. Studies of carving strokes were conducted in [14,15], to establish a correspondence between human results and robotic motion that approximates the same results. In [18], a step forward was made by adding some sensor-based robotic autonomy in the construction of wooden structures.

2.3. Games

Some video games provide creative interaction by replicating basic crafting aspects in the contexts of virtual building and decoration.

Creating virtual pottery using wheel-throwing and subsequent decoration is found in several games engaging creativity (e.g., 3D Pottery [19], Pottery Master [20], and Pottery Simulator [21]), albeit not exhibiting high levels of realism, nor addressing practical constraints.

In the adventure game genre [22], the prerequisite of crafting or recipe materials is addressed, by requiring them to be available for the execution of an action. Although recipes do not contain a simulation of how materials are treated, they provide constraints. A central concept in these games is the "recipe", or the representation of the knowledge necessary to transform a collection of needed ingredients (materials) into a new object. For example, a recipe for a pickaxe specifies two twigs and two flints as the necessary materials. Certain recipes regard only specific types of materials, such as a recipe for tailors that transform fibres into fabric or a recipe for blacksmiths that transform bulk metal into a sword.

Using human motion in gaming interaction has proliferated since the Wii controller. The Knitting Simulator 2014 [23] requires the manipulation of controllers that resemble knitting needles. The usage is simplified as needle motion is only used to advance a knitting animation. In [24], a VR controller is used to edit solids by revolution in wood-turning lathe crafting simulation. An architecture for integrating the Unity game engine as a platform for craft simulation is proposed in [25].

PhysX [26] is a physics engine middleware SDK for the development of gaming applications that are based on hardware acceleration to achieve real-time performance. It supports rigid and body dynamics and volumetric fluid simulation. However, it cannot simulate the generality of phenomena in the context of this work, as it does not support all of the material properties and damage models of interest in this work.

2.4. Serious Games

A serious game or applied game is a game designed for a primary purpose other than pure entertainment [27]. The idea shares aspects with simulation generally, including flight simulation and medical simulation, but explicitly emphasises the added pedagogical value through fun and competition.

Woodwork Simulator [28] recreates the experience of working in a carpenter's workshop. It provides reasonable approximations of the effect of virtual saws, drills, glue, chisels, and sandpaper on virtual wood. Educational uses are found in workspace geography and safety, training in the use of tools, and the planning of woodworking processes that implement specific designs.

In [29], a blacksmith's forge is simulated in VR providing simplified tool interaction that shapes metallic pieces parts using 3D controllers; the crafted structures can be 3D printed.

Counting and calculating tasks are intrinsic to the weaving of fabrics and wicker. In [30], these capacities are trained to make calculus for young students more interesting, intuitive, and educational on Native American Heritage.

In [31], glasswork actions are simulated to accustom to the weight, balance, and handling of a real blowpipe performed at a real glassblower's bench. A Mixed Reality system tacks human hands and illustrates the user against exemplar hand movements for that action.

2.5. Visualisation

Works that predict the visual appearance of crafted artefacts are found in the textile industry. Prominent examples are WeaveIt [32], Weaving Design Software, version 4.2.4.0, [33], ArahneWeave [34], pixeLoom [35], WeavePoint [36], and WIF Visualizer [37]. The 3D Knitting Simulation [38] 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. More relevant to handcrafted textiles, a physics-based heuristic model is used in [39] to predict the visual results of painting on fabric, using thin-brush dyeing. The simulator focuses on modelling 2D fluid simulation on fabrics to reduce the computational burden. The dyeing algorithm is based on an ink-wash painting algorithm [40].

2.6. Finite Element Methods

Realistic simulations of actions upon materials are found in the field of scientific simulation. Finite Element Analysis (FEA) [41,42] is a numerical technique that utilises the Finite Element Method (FEM) to simulate and analyse the behaviour of physical systems. FEA is the de facto standard in state-of-the-art physical simulations. The idea behind the FEA is to divide complex physical systems into smaller, simpler, and very local (or finite) elements. The behaviour of each element is predicted by mathematical equations that describe the physical laws governing an action.

Although widely adopted in modern mechanics and engineering, scientific simulation has been not widely applied in the domain of crafts. In [43], the formation of knots is studied using FEM. Mechanical models for fibres are proposed in [44] that account for elongation, bending and torsion forces, and the frictional contacts between them. In [45], 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.

Moreover, a broad range of studies exists on the mechanical characterisation of textiles (see [46–49] for reviews). Several pertinent works also focus on how textiles are to deform and distort when worn, e.g., [50–52]. The most relevant work to the purposes of this work is TexGen, version 3.13.1, [53], an open-source software for modelling the geometry of textile structures, as well as including textile mechanics, permeability, and composite mechanical behaviour. In the computations pertinent to the manufacturing of textiles, we use the TexGen simulator to model the 3D structure of fabrics.

2.7. Vibration Analysis

In industry, vibration analysis plays a crucial role in understanding the dynamic behaviour of structures and materials, such as accurately modelling the location of notches [54], or increasing the efficiency of lathe-based manufacturing methods [55]. Vibration analysis is integral to some traditional crafts, providing manufacturing and evaluation benefits.

Textile weaving relies on rhythmic beating, which generates vibrations that ensure the even distribution of threads and the tightness of the fabric. The uniform application of vibrations during weaving enhances the quality and durability of the textile [56]. Traditional weavers use tactile feedback from the loom's vibrations to guide their work, demonstrating the critical role of vibration analysis in achieving precision and consistency.

The crafting of musical instruments, particularly string instruments, is dependent on understanding and manipulating vibrations. The resonance and sound quality of instruments like violins and guitars are directly linked to how materials respond to vibrations during crafting and playing. In traditional Japanese drum-making, the tensioning of the drumhead involves careful manipulation of vibrations to achieve the desired pitch and tonal quality [57].

Traditional East Asia papermaking involves using vibrations to settle pulp fibres uniformly on a screen, which is crucial for producing even, high-quality paper. Specifically, controlled vibrations enable artisans to manipulate the paper's thickness and texture [58].

In contrast to industrial tasks where electronic sensors and computers are used, in traditional crafts, vibration analysis is performed by the perception and cognitive functions of the practitioner rather than electronic sensors. In musical instruments, perception and cognition are employed; it is the recognition of sound quality, in pottery in the recognition of haptic texture, and in papermaking in the proprioceptive control of fibre shaking. Such human sensory and cognitive aspects are integral in crafts but beyond the scope of this work and are revisited in the discussion in Section 6.

3. Simulation Elements

In this section, we introduce the elements that govern the representation and simulation of crafting actions. All physical quantities in this virtual world are measured in the SI system.

3.1. Action Types

The goal of this work is to create a semantic and generative representation approach for crafting actions. A classification of actions in four types is proposed that is functional and at the same time semantic. These are (1) subtractive, (2) formative, (3) interlocking, and (4) additive actions. In Table 1, representatives of these actions are provided, along with the types of workpieces used and the mechanical methods used for their simulation. Subtractive actions refer to the removal of the material or the partitioning of a workpiece into smaller pieces. Subtractive actions are simulated using the damage model of the material which describes the behaviour of the material under mechanical stress that surpasses its yield point. Various damage models, each one suited to specific materials and damage mechanisms. Forming actions change the shape of the workpiece while preserving its mass. They are simulated based on the plasticity and elasticity properties of the workpieces, while often these properties are enhanced through heat or wetting. Interlocking actions join two or more workpieces together in a way that the identity of each piece is retained after the interlock, such as in spinning weaving textiles from threads or interlocking parts using a nail or a fastener. Besides plasticity and elasticity, friction plays a central role in these actions because it keeps the interlocked pieces together. Additive actions differ from interlocking in that the added materials are joined into a new body that is considered as a whole, such as building a wall with mortar or glazing ceramics. The most relevant material properties are the plasticity and cohesive properties of materials, as well as the stability of the assembly.

In addition to the basic actions mentioned above, we consider two auxiliary actions: (1) moving objects in space and (2) waiting for time to pass.

Table 1. Action types.

Action Type	Representative Action	Simulation Properties
Subtract	Remove bulk material	Damage model
	Split	
	Cut, tear	
Form	Casting	Plasticity, Elasticity
	Shaping	
	Bending	
	Folding	
Interlock	Weaving, Spinning	Elasticity, Plasticity, Friction
	Joining	
Add	Placing	Plasticity, Cohesion
	Adding	

3.2. Space and Time

In a simulation, events take place in virtual time and space. Simulated time is represented by a time interval. Computationally, this interval is discretised in time frames and the state of the simulated elements is stored individually and chronologically for each time frame. All elements can be time-variant. In practice, the rigidity stability and apparent motion of structures and objects are assumed to reduce computation at a reasonable approximation. The simulated time is represented by a time interval and time-discretisation parameters.

The 3D models used for tools and motion recordings exhibit variability because they stem from a wide range of 3D digitisation methods or databases. Unit transformations are treated by the multiplication of v's coordinates with an appropriate scalar. Reference system incompatibilities are treated by a pose transformation P for each object in the simulation, where P comprises R and T, and 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. This transformation is applied to each node v (a 3×1 matrix) as $R \times v + T$, where '×' denotes matrix multiplication.

3.3. Environmental Conditions

Environmental conditions determine affordances that enable or disable the possibility of treating materials using tools. The conditions of primary interest are gravity, temperature, and humidity. In this work, the focus is on properties related to material transformations, although the existing additional ones relating to the well-being of practitioners (e.g., noise, lighting, temperature, and ventilation) are out of the scope of this work. In this work, the following environmental conditions are of relevance:

- Gravity is always simulated, determining object stability, self-weight part deformations, and fluid behaviour.
- Temperature directly affects the viscoelastic behaviour of a wide range of materials. Heat is also an agent of dryness or chemical changes that lead to new material properties.
- The wetting of soil-based materials affects workability and cohesive properties.

3.4. Material Properties

Material properties express the functionality and manufacturability of materials. They may be functions of one or more independent variables, some of them being environmental conditions.

Each material property is represented as a vector of one or more values. Most materials are isotropic; that is, their properties are equally expressed in different directions. When this approximation is insufficient (e.g., for wood or marble), materials are called orthotropic and treated independently per direction, and a definition of the intrinsic orientation of the material within the workpiece is additionally required.

In Table 2, we classify material properties according to the affordance they avail and the action types defined in Section 3.1. Density is always accounted for as it determines the weight and momentum of objects. Young's modulus measures how stiff a material is by comparing the amount of force applied to an object with how much it deforms. It is used for materials under stretching or compressing and is measured in Pascals (Pa). Elastic modulus is a broader term that includes Young's modulus along with other measures like the shear modulus (resistance to twisting) and bulk modulus (resistance to volume changes).

Table 2. Classification of material properties.

General (Move)		
Density	Mass per unit volume.	kg/m^3
Friction	The ratio of the force of friction between two bodies and the force pressing them together (normal force)	Unitless
Strength (Subtract, Form)		
Hardness	Ability to withstand localised permanent deformation and/or resistance to deformation.	Pascal
Tensile, compressive, shear strength	Parameters that describe material strength under different loading conditions.	Pascal
Ductility	Ability to undergo significant plastic deformation before rupture or failure, measured by elongation at break and reduction in area.	Unitless
Plasticity and Elasticity (Form, Interlock)		
Elastic Modulus	Resistance to non-permanent, or elastic, deformation.	Pascal
Young Modulus	Stiffness of material.	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.	Unitless
Toughness	The ability to absorb energy and deform plastically before fracturing.	$Joules/m^3$

Ductility is a physical property of a material that describes its ability to be stretched, pulled, or drawn into a thin wire or thread without breaking. Ductility under tension involves tensile stress (pulling apart), while ductility under compression involves compressive stress (pushing together) [59]. Besides choosing the appropriate material property for the action, when studying ductile phenomena, the origin and pre-processing of the specific material need to be considered as fine-grained materials achieve higher compressive extensibility compared to annealed materials [60].

In some cases, we choose to disregard some material properties for simplification of simulation. First, properties irrelevant to the mechanical actions are not considered, such as electrical or magnetic properties. Second, properties related to the deformation of objects are ignored when known to be insignificant; the corresponding objects are regarded to be rigid. Such cases regard tool wear. For example, during the study of a cutting action, we are not interested in the microscale wear of the hammer that cuts a piece of wood. Still, however, density is considered, so that their mass, acceleration, and momentum are computed.

3.5. Objects

Objects are tools and materials, the latter eventually transformed into products. All objects have shape. Objects can be composed of multiple parts; in this case, an individual shape is defined per part. The shape S of an object or an object part at a time frame is represented as follows: let S = (V, G), where V is a 3 × N matrix of N floating-point locations that represent the nodes of a volumetric mesh and G is a matrix of connectivity indices on these nodes that indicate the M finite elements in space. These elements may be hexahedra or tetrahedra and accordingly, B's dimensions are either 6 × M (tetrahedra) or 12 × M (hexahedra). It is pointed out that the motion of objects is represented through the change of coordinates in V.

3.5.1. Tools

The shapes of tools or tool parts are designed to afford specific functionalities. In [61–63], tools are classified according to their use in (a) cut, (b) pinch, or grip, (c) drive, (d) strike, and (e) be struck. In Table 3, we propose an association of tool classes with tool shapes and mechanisms and the action type they are used in. The rationale for this classification is described below.

Table 3. Association of tool types with their shape characteristics and actions.

Tool Type	Shape	Indicative Tools	Action Class	Mechanism
Cutting	Tapered edge	Blades	Subtract	Wedge
	Jagged edges	Saws	Subtract	
Struck	Tapered edge	Chisels, Gouges	Subtract	
Gripping	Pair of jaws	Tweezers, Pliers, Wrenches	Move, Interlock, Subtract	Pressure, friction
Striking	Flat face	Hammers	Subtract, Form, Interlock	Momentum
Driving	Tip	Screwdrivers	Interlock	Torque, lever, friction.
	Profile	Wrenches	Interlock	

The characteristic of cutting tools is their tapered edges. Cutting tools employ the wedge simple machine to concentrate a force at the tapered edge and its sides. When the pressure built at the edge exceeds the yield point of the material, it breaks. The lateral forces of the wedge push apart the material further increasing the tension at the cut. Tools that are struck such as chisels follow the same principle of operation. Scissors are cutting tools that use two wedges in combination with a wheel and axle.

Sticking tools have flat faces and convert dynamic energy into momentum and eventually force. They are used to either deliver force directly on a workpiece or strike another tool.

Gripping tools are double-handed and have a pair of jaws. To grip, their shape is changed making their jaws come closer and concentrate the force from their handles to their jaws. The pressure and friction stabilise the workpiece within the grip. Tweezers tools rely on the elasticity of the material they are made. Pliers are made using a wheel and axle and two levers. For wrenches and vices, additionally, use a screw simple machine.

Driving tools are used in conjunction with screws and use torque to drive them. They are distinguished into screwdrivers and wrenches, which are characterised by a tip or a profile, respectively. Screwdrivers are inserted into the drive recess of the screw head, applying torque through the centre axis of the screw. Wrenches have a compatible profile that fits around the external flats of the (hexagonal) screw head, enabling the application of torque from the outside edges.

Overviews of the mechanical analysis of these tools can be found in [64,65].

3.5.2. Workpieces

Depending on the action, workpieces may be required to have a specific shape. In weaving, workpieces are strings. In interlocking components, screws require compatibility with the tools and possibly the screw path. In boatmaking, plies are bent and shaped. In masonry, bricks are built. In terms of representation, products are processed workpieces at a final or intermediate processing step. The product of a processing step is the workpiece of the succeeding processing step.

Depending on the action, the resultant workpieces are represented differently. That is, in interlocking actions, we retain the shape and identities of the interlocked objects. In contrast, in additive actions, the resultant workpiece is treated as a new whole. In subtractive and shaping actions, we consider the workpiece to have the same identity but with a new shape.

3.6. Causing Entities

Causing entities are the phenomena that bring changes in the state of objects and materials in the scene. In the crafting context, we consider forces, motions, and time.

3.6.1. Forces

Practitioners employ forces to form materials, cut or join parts, drive screws, or maintain stability during material treatment. The application of a force is an event, which occurs in space and time. Forces can be time-dependent, in which case the properties below are individually defined peer time frames.

Forces are classified into linear and rotational (torque). Linear forces are modelled using F, [v, A], where v is $[v_x, v_y, x_z]^T$, R^3 is the direction of the force in Cartesian coordinates, and t is the time interval in which the force is applied. Torque forces are modelled similarly, as τ, [F, r, A], where F and A are modelled as above; r is the perpendicular vector from the axis of rotation to the location where the force is applied.

The application of a force is modelled to occur across a spatial profile, let A, which identifies the finite elements upon which the force is exerted. A is a matrix of finite element IDs and may contain a single point, the points of a surface area, or all the locations of an object; the latter is called a “body force”, e.g., gravity is an omnipresent linear and body force for all objects.

3.6.2. Movements

Another way to represent crafting actions is through the movements of objects. Admittedly, object motions occur due to the application of forces; however, in some cases, we cannot easily measure or are not interested in modelling these forces. Cases where we cannot easily measure forces are those where we wish to simulate an action captured by video or motion capture sensors. In some other cases, we are not interested in modelling the forces, such as when an electrically powered tool is used, such as a lathe, a potter’s wheel, or a nail/staple gun.

For rigid objects, motion v, [T, R, t] is modelled using the translation T and rotation R in space, where R $[r_x, r_y, r_z]^T$ is a rotation in SO(3), and T$[t_x, t_y, t_z]^T$, a translation, in R^T, respectively. For deformable objects, motion is modelled in the same way but per each finite element that the body comprises. Like forces, motions are state variables that are individually represented per time frame in time interval t.

3.6.3. Time

In many crafts, waiting is a necessary, intentional step. It is essential for wet materials to dry, adhesives to solidify, and ceramics to be sufficiently fired. Waiting is modelled as the "null" action, occurring in time interval t.

4. Action Modelling and Simulation

The organisation of entities and their properties provided in Section 3 is utilised to model actions and define the properties needed to simulate them. The purpose of simulation archetypes 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 tools, materials, and practitioner motions.

4.1. Modelling

As our approach aims to provide a link between semantics and mechanics, for each action, we provide its reference in a hierarchical word thesaurus, namely the Getty Arts and Architecture Thesaurus. We selected this thesaurus because it is well-established scientifically, it is the most relevant to crafts, it is multilingual, and, most importantly, it is hierarchical. In this thesaurus, the terms incising, splitting, drilling, and tearing are found under the <subtractive processes and techniques> class. The references for the names of craft actions utilised in this paper can be found in Appendix A.

The action templates that are modelled are the Additive, Subtractive, Interlocking, and Forming transformations. Before presenting these, we first model auxiliary actions, namely Moving, Waiting, and Weighting.

4.1.1. Weight Models

The weight, as a heaviness attribute, of objects in the simulated elements is always considered. This is implemented as a bodyweight force, which is applied to each finite element in the scene. Over time, and depending on the stiffness and friction of involved objects, this may lead to different results. Rigid objects may fall arbitrarily or slip upon an inclined plane.

4.1.2. Waiting Action Models

Waiting is the "null" action; that is, no motion or forces are simulated. During the waiting interval, changes in temperature, wetness, or other might take place. Moreover, the pose of objects may change, depending on their placement, friction, and weight. Waiting is denoted as O' = Wait(O), where O and O' are the younger and older versions of the object, respectively.

4.1.3. Moving Action Models

Moving objects, particularly tools, machines, or components, change (solely) position. They are modelled using motion during a time interval and denoted as O' = Move(O), where O is the object in its initial pose and O' is the object at its new pose.

Moving actions are classified into loading and handling actions. The first is afforded by moving and transporting equipment, for shovelling bulk material and the second by holding and gripping tools, for pinching or gripping solid objects.

Loading simulations are based on the friction, stability, and inertia of the material upon the loading tool during the action. Handling simulations involves grip and lever mechanics. Solid and bulk materials are simulated using solid or particle modelling, respectively.

4.1.4. Subtractive Action Models

Subtractive processes and techniques are characterised by the removal of material. They are denoted as O_1, $O_{2,}$ . . . O_n = Subtract(O), where O is the original object, O_1 is the resultant object, and O_2 to O_n the removed fragments.

Subtractive actions damage the bonds that comprise a workpiece as a whole to subtract material from it. They are afforded by the damage of materials under pressure and simplified using cutting, gripping, striking, or struck tools. This damage has a different expression in different material types and conditions, in terms of damage initiation and propagation across space and time. Damage models predict this expression for specific classes of materials. In this work, we primarily consider

- The Orthotropic Damage Model [66] for orthotropic materials and, specifically, wood, wicker, or other fibrous materials [67–69] enables damage simulation in independent directions.
- The Cohesive Zone Model [70,71], for crack initiation, propagation, and cohesive failure in brittle and anisotropic materials, such as stone, marble, and glass.
- The Johnson–Cook Model [72,73], for simulating ductile materials, typically metals, accounts for hardening and includes the effects of strain rate and temperature.

This work does not cover all existing damage models but focuses on those most relevant to traditional crafts and the materials used in their context. As manufacturing capabilities are modernised, new materials become available to craft practitioners, as well as new methods for their treatment. For example, the SC11–TNT model [74] is associated with titanium alloys, which were not traditionally used in crafts. As shown in [75], the damage of Ti alloys that contain Zn and Cu can be modelled using the SC11–TNT, which exhibits the potential to be extended to other ductile materials, with appropriate modifications and calibration. Thus, the proposed criteria are to be used as a first approximation and be refined with more specific ones, when pertinent knowledge of the materials is known.

Damage models require precise calibration of model constants using combined experimental and numerical calibration approaches [76,77]. This process involves gathering detailed experimental data across different strain rates, temperatures, and loading conditions and then performing finite element analysis with initial parameters. In this work, we use constants and models found in well-established online resources and the literature. However, for simulation accuracy, the constants of the particular materials should be calibrated, to achieve accurate and reliable modelling results.

Table 4 summarises the damage models considered in this work and includes additional references for the listed models. All model implementations were provided by the Simulia Abaqus software, version 6.23-1, [78].

Table 4. Summary of utilised damage models.

Name	Description	Mathematical Model Name	References
Orthotropic Damage	Describes the mechanical behaviour of materials that exhibit different properties along three mutually perpendicular directions (orthotropy). It typically includes damage evolution laws specific to different material directions.	Hooke's law for orthotropic materials	[66–69,79–82]
Cohesive Zone	Utilised to simulate the behaviour of cracks and interfaces by representing the traction-separation relationship. This model defines the behaviour of a material until complete separation occurs.	The constitutive behaviour of crack opening is governed by a traction-separation law, the Cohesive Law	[71,72,83–85]

Table 4. *Cont.*

Name	Description	Mathematical Model Name	References
Johnson–Cook	Describes the flow stress of materials under varying strain, strain rate, and temperature.	Flow stress equation	[72,73,86–89]

Examples of subtractive actions are wood sculpting, stone carving, metal engraving, and other crafts.

4.1.5. Forming Action Models

Forming actions induce the relocation of material within a piece of material which, as a result, changes its shape. They are denoted as $O' = \text{Form}(O)$, where O and O' are the original and deformed objects, respectively. Forming is a mass-preserving transformation.

They are afforded by the capacity of materials that undergo shaping without breaking, thus requiring malleable and formable materials. They are classified into methods that require the material to be (a) viscous or solid, in which workpieces are shaped by forces exerted upon its surface or (b) liquid, in which materials are led to moulds to solidify. A special case of (a) is folding, where sheets of material are bent along a, typically straight, line. This transformation has lower dimensionality, simpler representation, and multiple applications. As a result, specialised simulation studies exist in a wide range of scientific domains.

The primary condition of interest is plasticity because it expresses how easy it is to shape the material. For (a), elasticity shows if the shaping action was effective, that is, the extent to which the workpiece resumes its prior shape after the shaping action. For (b), viscosity shows how easy it is to lead the material into moulds. Depending on the material, these material properties are influenced by heat and humidity.

Elasticity for small deformations is considered linear (i.e., following Hooke's law); however, more realistic, non-linear, approximations of individualised per-material models are required for larger deformations. The plasticity of solids is more specifically described for metals [90], rocks [71], and clays [91,92]. For mainly solid materials, models are employed and creep models predict the slow deformation of a material under constant stress and temperature [93,94]. For mainly fluid materials, fluid flow and heat transfer [95], solidification and melting [96–98], and thermal-fluid coupling [98,99] models are employed.

Examples of forming actions are found in ceramics, glassblowing, blacksmithing, moulding, or bending plies of wood to make boats.

4.1.6. Additive Action Models

Additive and joining processes and techniques unify parts in a whole. The regard built or layering of materials using cohesive properties of materials, which are modulated by heat or wetness. They are denoted as $O_3 = \text{Add}(O_1, O_2)$, where O_1 and O_2 are the added materials, and O_3 is their composition. Composition O_3 is treated as a new whole, which may have different properties of interest than its members. Nevertheless, additives are modelled incrementally following the real process.

Additive mechanisms are afforded by cohesive materials that unite pieces in a body and the stability of individual piece placement. Cohesive behaviour has been studied for a wide variety of materials and, thus, accurate instructions for their preparation and application are available. Cohesive Zone Models [70,71] simulate the bonds between cohesive elements and surfaces. Depending on the material, cohesive properties are induced by heat or wetting.

Examples of additive actions are joining pieces of metal together in metalsmithing, building walls with bricks and mortar, or adding a layer of glaze to a ceramic pot.

4.1.7. Interlocking Action Models

Interlocking actions are subclasses of additive and joining processes and techniques, which join separate pieces in a composition where pieces retain their identity and properties. They are denoted as $C = \{O_1, O_2\} = \text{Interlock}(O_1, O_2)$, where O_1 and O_2 are the original pieces and $\{O_1, O_2\}$, or set C, is their interlocked composition. The composition has motion constraints which lead to rigid or flexible interlocks.

Rigid wholes are made from stabilised parts held together by friction and tension among them. Deformable wholes are made either from rigid or flexible parts. When made from rigid parts, kinematic constraints predict the behaviour of the whole. When made from flexible parts, elasticity and plasticity are additionally considered.

In practice, interlocks come after another action, such as forming or moving, which brings the pieces in place, such as deforming metal to interlock the links of a chain, driving a nail to interlock it with a piece of wood, or adding a weft in a fabric. Examples of interlocking flexible parts are found in textiles, strings, and wicker.

Examples of interlocking rigid parts in a rigid result are driving a screw, hammering a nail, or connecting wood pieces using dovetail joints. Examples of interlocking rigid parts in a moveable result are chains, hinges, and music boxes. Examples of interlocking flexible parts are strings, ropes, fabrics, and wicker.

4.2. Simulation

We utilise a FEM simulation engine, specifically Simulia Abaqus 6.23-1, to create generative mechanical models in software. Material properties are looked up in MatWeb [100]. Only the material properties of interest to the actions to be simulated are considered.

4.2.1. Input

The input to the simulator contains the elements (Section 3) and a schedule of the actions (Section 4) to be simulated. This input is encoded in a simulator input file. Object shapes are modelled usually in the form of hexahedra and at a scale relevant to the simulated action (i.e., usually 1 mm^3). The main input entities are

1. Objects as separate parts, as well as indications if considered rigid or static.
2. Materials and their properties.
3. Transformations that place objects in the virtual scene.
4. Gravity and any environmental conditions prescribed.
5. Causing entities and their scheduling.
6. Definitions of simulated time intervals and their discretisation.

Typically, this input is produced using a GUI that provides design tools, data input facilities, and access to the computational models. In this work, we are creating templates using a GUI to create input files that we use as templates for specific actions. In this way, we create action variants by modulating the contents of these templates, using simple computational means, i.e., a computer program (script) that generates this file, by instantiating action templates with specific objects and parameters. This is useful for automatically modulating parameters and combining multiple actions into processes.

4.2.2. Execution

The input information is sufficient for any FEM engine to carry out. In this work, the Simulia Abaqus is employed. The input is encoded in the appropriate (.INP) file format. Input files are prepared in a human-comprehensible version (i.e., text) of this format. The input file contains the information for the reproduction of each simulation. The execution of the simulation takes place using the FEM engine and the input file and is executed in parallel if multiple processing nodes are available.

4.2.3. Output

An output file contains the state of the objects at each simulated time frame. This state regards the shape S of each simulation element, as well as the values of forces developed in the simulation. Volumetric formats are used to encode the input and output of action simulation in STEP format [101].

The output can be visualised in conventional and immersive virtual environments. Scientific visualisation involves 3D rendering of FEM meshes over time. Simple visualisation methods, however, require only the outer surface of objects. Export of object surfaces is provided in the Wavefront OBJ File Format [102].

The output does not contain semantic information about the connectivity of objects as a whole, e.g., whether a piece of material has been divided into two pieces or not after a cutting stroke. This information has to be computed or judged by accessing the output file or its visualisation, respectively.

5. Use Cases

In this section, the results of applying the simulation archetypes are presented. The use cases are representatives of the action types defined earlier. The visualisation of results follows the following conventions. All simulations were formulated using Simulia Abaqus [78], a software suite for Finite Element analysis and simulation, which provides implementations of all the aforementioned physical models (in Sections 3 and 4).

In the figures below, multiple frames (usually three) are used to present an action, from the same viewpoint using a perspective virtual camera. They are chronologically juxtaposed from left to right. If an action is shown in more than one row, then the row order is top to bottom. The finite elements of the simulated bodies are rendered as opaque meshes. The colour of elements represents the mechanical stress occurring in each element.

5.1. Weight

Gravity is considered in all simulations. The first example shows a metallic workpiece gently placed upon a rigid planar surface. The simulation is shown in Figure 1 (top row). In the bottom row of the same figure, is a representation of the free fall of four workpieces (from left to right): a metallic sphere, a wooden sphere, a metallic cube, and a wooden cube. Depending on the initial posture and material, the workpieces exhibit variations in their bouncing behaviour.

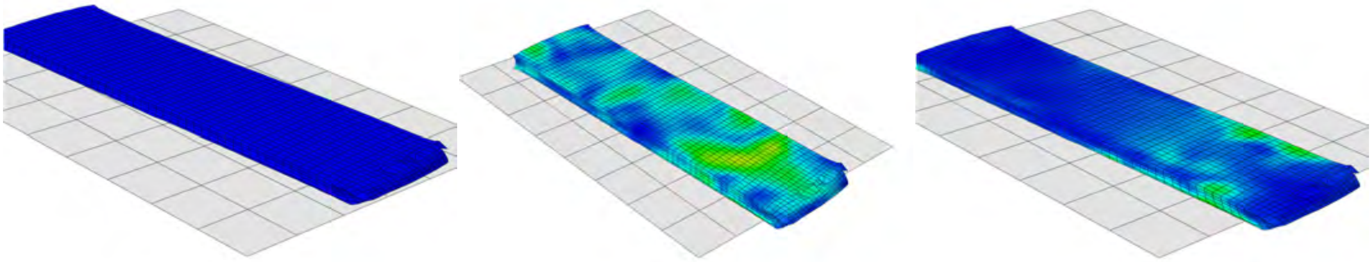

Figure 1. Simulation of a metallic workpiece left from a small height on a rigid planar surface under the influence of gravity, showing it falling, bounding a few times, and eventually resting.

5.2. Subtractive

Subtractive actions are distinguished by the way damage is brought to the material. The first type regards methods that use a wedge-shaped tool to concentrate energy to breaking regions. These cases also require stability of the workpiece, usually provided by a hand grip or vice. In simulation, it is implemented by applying pressure to its sides. The second type regards the application of forces directly to the material, such as when tearing it.

5.2.1. Incising

Incising is a superclass for cutting, carving, and engraving. The following incision variants are simulated in Figure 2. Cutting (top): the tool follows a straight-line trajectory in the horizontal direction. In the vertical, it follows a sinusoidal descent and assent coming in contact with the material in ~80% of the time interval. Engraving (middle): the tool follows a straight-line trajectory in the horizontal direction. Carving (bottom): stroke is for a chisel which is simulated; initially, the tool is struck perpendicularly to the surface and then the tool motion includes a rotational component. In this last example, tool motion is obtained using motion capture and obtained from [103]. This last example shows the potential of using motion trajectories for tools, as acquired from Motion Capture recordings.

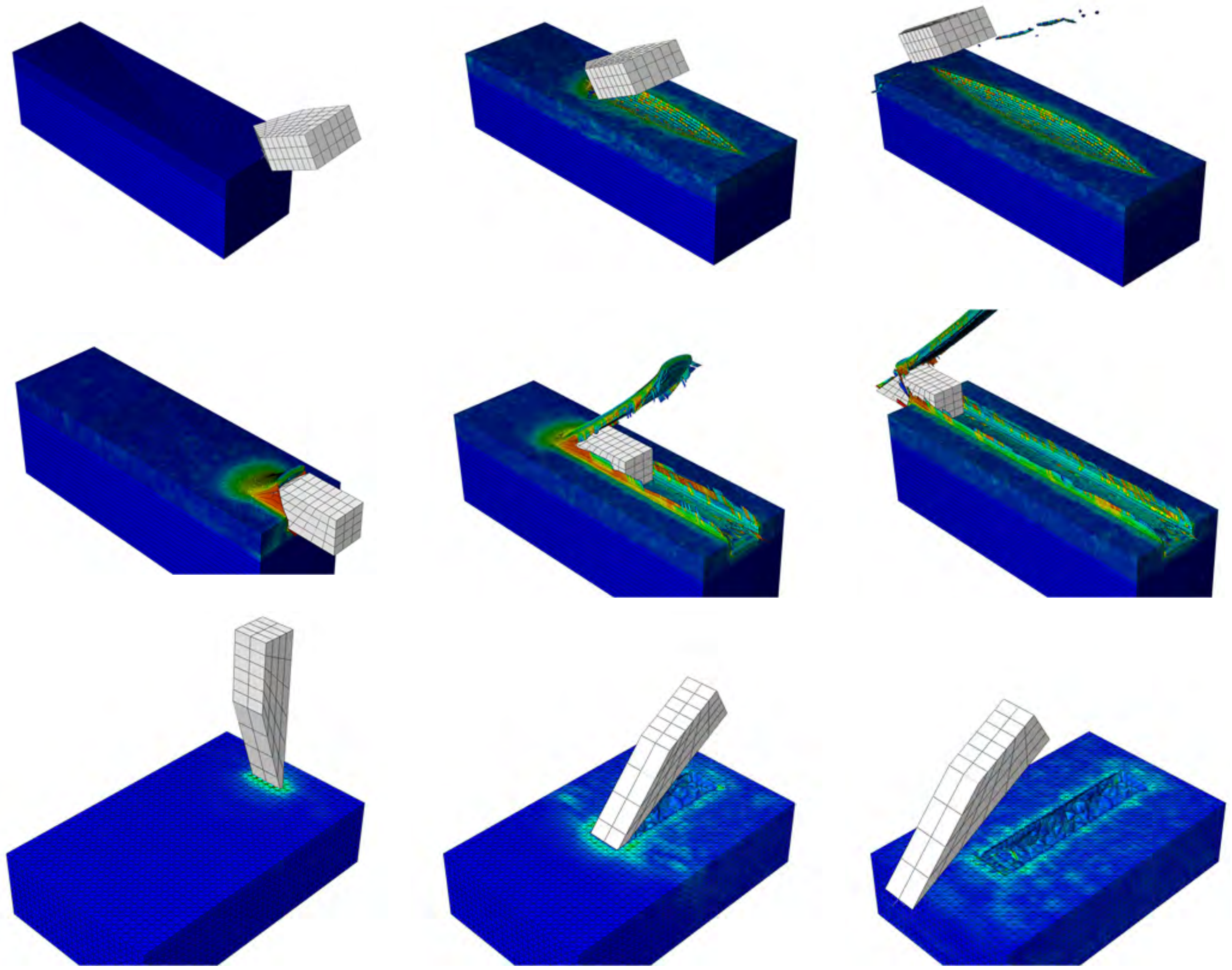

Figure 2. Simulation of three incision techniques. **Top**: Cutting, where the tool follows a straight-line horizontal trajectory, with variable height. **Middle**: Engraving, featuring a tool that follows a straight-line horizontal trajectory in the horizontal direction. **Bottom**: Carving, where the stroke of a chisel is simulated. The tool is initially struck downwards and perpendicularly to the surface and, subsequently, moved upwards in a rotational motion.

The carving tool movement from Figure 2 was utilised and repeated multiple times, in Figure 3. The tool movement was guided to create a sinusoidal pattern on a surface by the iteration of unit carving strokes. While following the sinusoidal line, the tool is locally rotated so that its sharpest edge is perpendicular to the tool's motion.

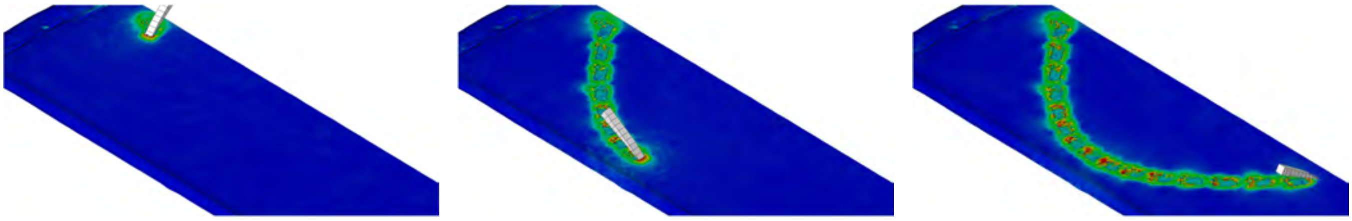

Figure 3. Simulation of repeated carving strokes on the surface that create a sinusoidal pattern.

5.2.2. Splitting

Splitting of a ply of material using a wedge-shaped tool. The purpose is to demonstrate the interoperation potential with external reasoning methods. In a cutting process, the stroke is repeated until the workpiece is cut. We substitute the counting of the resulting parts by the practitioner. This is implemented by a CCL graph-connectivity method (e.g., [104,105]) to determine if the workpiece remains a connected solid or whether it has been split.

The virtual workspace contains a ground plane and two supporting structures, all static and rigid. The tool is rigid and made of steel. The causing entity is a brief perpendicular force on the back face of the tool as if struck by a high momentum body, pushing it forward, and concentrating pressure at the contact boundaries between the two bodies. In the example, the template is twice applied to simulate two strokes of a cutting tool as the workpiece was not cut by the first stroke. In both cases, the workpiece is split after the second stroke.

We investigate the type of material. The ply material is aluminium and second wood, in conditions 1 and 2, respectively. The simulations of conditions 1 and 2 are shown in Figure 4 and Figure 5, respectively. The figures show that mechanical stress increases at the tool's edge until the workpiece breaks. During the cut, the wooden ply bends more than the metallic. Correspondingly, the metallic part is distorted at the contact regions with the supports. When the workpiece is split in two, the metallic parts bounce on the ground plane and hurl into space, creating a safety risk.

5.2.3. Turning

In turning, materials are shaped by subtraction during their rotation by a lathe. Turning techniques are afforded by the wedge-shaped tools and subtractive mechanism as carving, but in turning the material is not static but rotates about an axis. Electric lathes provide sufficient power for constant angular velocity and, thus, the induced rotation is simulated using rotational motion.

Tool motion is constrained by a tool rest that prevents the tool from being carried away by the rotating material and being safely pushed against the rotating surface. The tool is a wedge-shaped chisel and has the density of steel. The tool rest is beam-shaped, rigid, and static. In Figure 6, the simulation is shown.

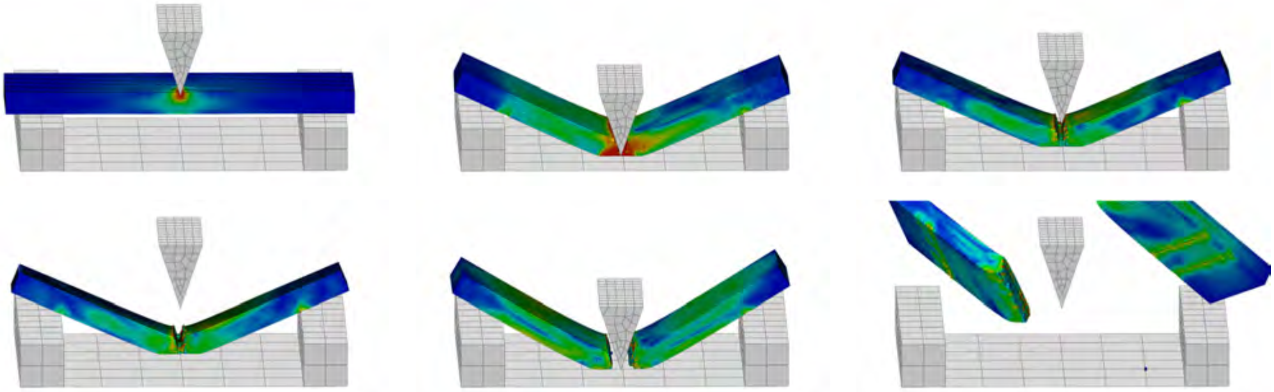

Figure 4. Simulation of splitting an aluminium ply using a wedge-shaped tool.

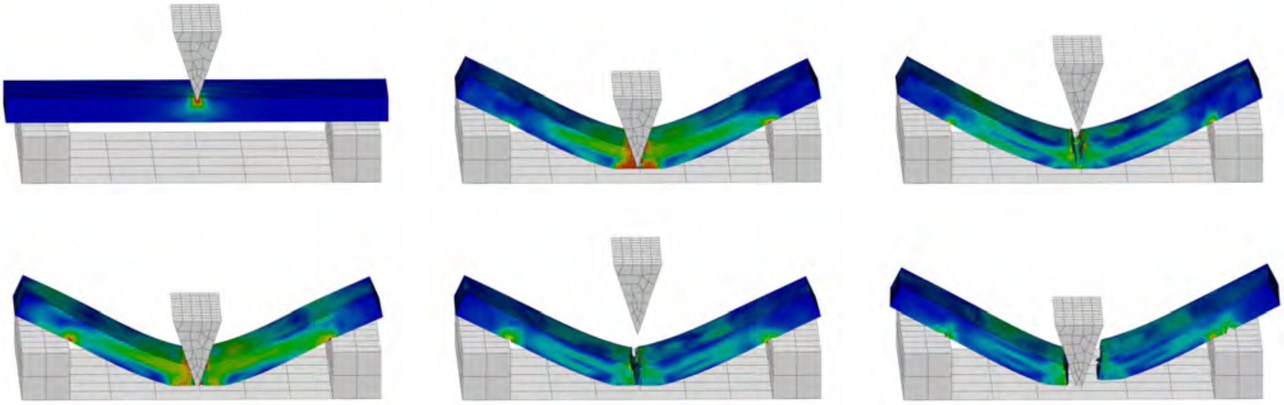

Figure 5. Simulation of splitting a wooden ply using a wedge-shaped tool.

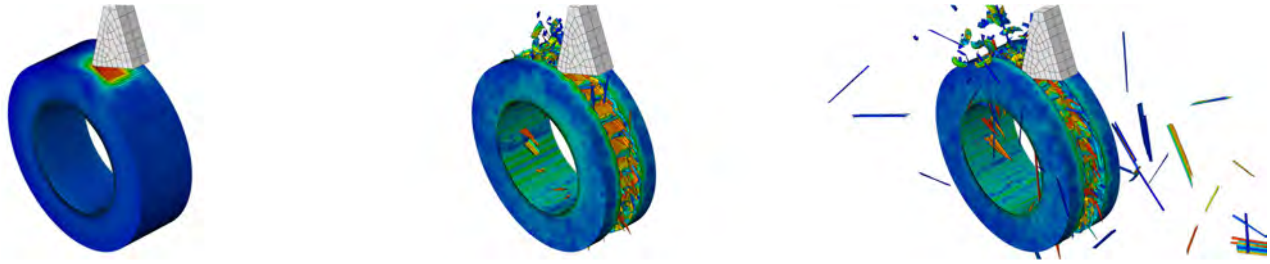

Figure 6. Simulation of turning using a lathe and a wedge-shaped tool.

5.2.4. Drilling

Drilling uses a sharp tool to create tubular holes in solid workpieces. Drilling is similar to turning but now the material is stable and the tool is rotating. Drills may be hand-powered or electrically powered and induce tool rotation using a wheel and an axle. Thus, as in the case of turning, the tool motion is modelled using angular velocity and a force that models the pressure exerted by the practitioner. The drilling tool tip bears threads to push material away and has a sharp wedge-shaped tip. In Figure 7, the simulation is shown for an elementary drill tool.

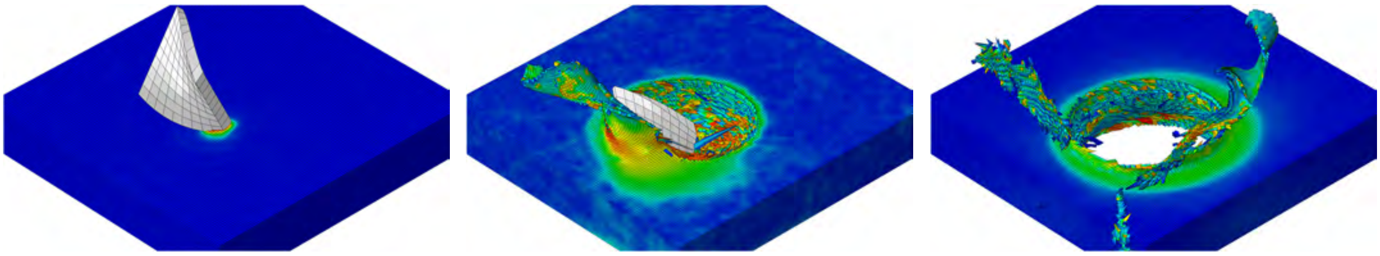

Figure 7. Simulation of drilling using a rotating tool.

5.2.5. Tearing

Tearing actions are afforded by at least two forces in (approximately) opposite directions that increase mechanical stress until the damage condition is met at some part of the material. In the example, such forces are exerted on the two edges of a thin sheet of aluminium foil.

In this example, we use the simulation template to investigate the way that the workpiece is torn, depending on the direction of the forces, in three conditions. The way that these forces are exercised determines the location where the material tears. In all conditions, the two forces are equal in magnitude and opposite directions. The simulation results are shown in Figure 8. In condition 1, the two forces are linear and the workpiece is thus torn symmetrically. In conditions 2 and 3, a rotational, torque component is added to the force direction. In condition 2, this component is rotational and about the major axis of the workpiece (horizontal in the illustration), providing a twisting effect in the result. In contrast, in condition 3, the rotational component is perpendicular to the surface of the workpiece (vertical in the illustration), providing a much more precise and linear tearing. This last condition simulated the tearing of aluminium foil as if the practitioner would rotate his/her right-hand wrist while pulling it apart.

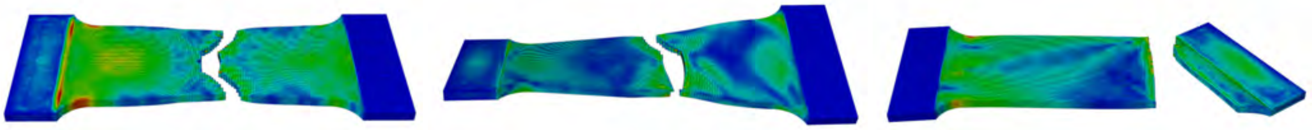

Figure 8. Simulation of tearing an aluminium foil sheet for three conditions. Condition 1 (**left**): Linear forces result in a symmetrical tear. Condition 2 (**middle**): Forces include a rotational component about the major axis of the workpiece (horizontal). Condition 3 (**right**): Forces include a rotational component perpendicular to the workpiece surface (vertical).

5.3. Additive

5.3.1. Adhesive Assembly

The stability of structures due to gravity is sufficiently covered by conventional physics-based engines used in gaming. The assembly of structures without adhesives relies on the stability of the assembly during and after its construction. Simulations use the shape, load, and spatial arrangement of pieces to predict the stability of a structure given its weight as well as its strength to external forces.

To increase the stability of assembled structures, adhesives are intermediated between pieces. These are usually glue or mortar which become semi or completely liquid with water and solidify through evaporation. The addition is complete when the adhesive solidifies and unites parts in a whole, meaning that additive actions using adhesives are usually followed by a waiting action.

The stability and strength of the assembly are determined by the specific properties of the adhesive as well as the weight and configuration of the pieces. Simulation can be used to evaluate and improve the stability of designs. Such simulations are solved through general contact (i.e., collision detection) and gravity constraints and are used to predict the stability of structures under pressure or vibratory motion (i.e., an earthquake). In Figure 9, we demonstrate the effect of adhesive material by moving the second from the bottom element of a stack of workpieces. In the top row, simulating the use of concrete as mortar makes the top bricks stay in place, while in the bottom row, its absence makes the stack collapse.

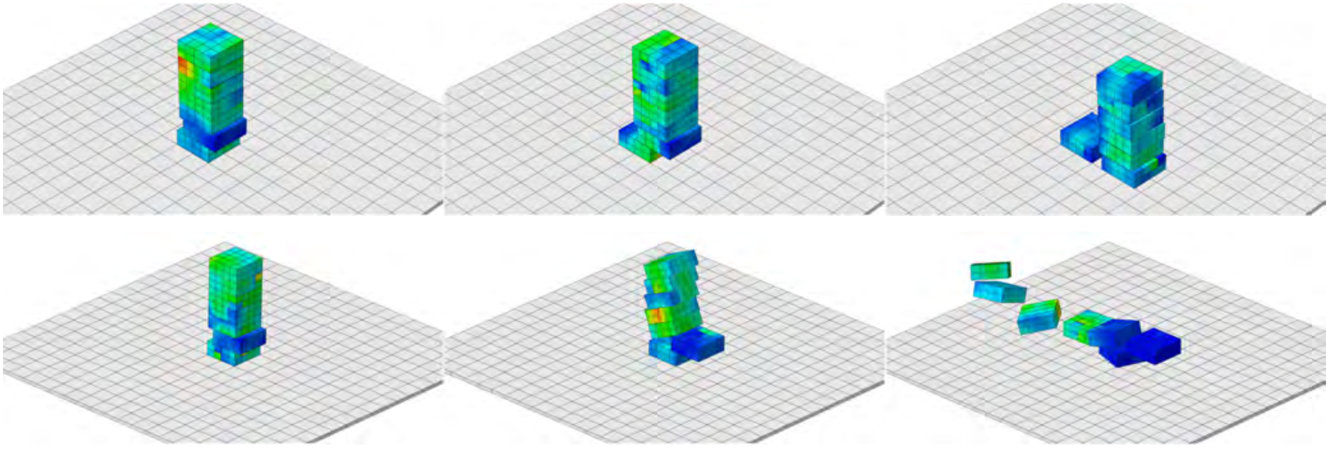

Figure 9. Simulation of the stability of a stack of workpieces, when the second from the bottom is dislocated, with the use of mortar (**top row**) and without (**bottom row**).

It ought to be noted that a lack of adhesive does not always mean a lack of stability. For example, dry-stone walling [106] is used to create very stable structures constructed from stones without any mortar. Binding is obtained through the use of carefully selected interlocking stones.

5.3.2. Metal Assembling

Metal assembling processes and techniques, such as welding and soldering, require heat so that the joining material liquidates and, when solidified again, turns the joined components into a whole body. As their FEM simulation has been extensively studied by the industry, a series of works offer simulation methods for joining metals in general [107] or specific metallurgic additive methods in particular, e.g., crimping [108], soldering [109], welding [110].

5.4. Forming

5.4.1. Debossing

Debossing creates recessed relief images and designs in materials. A debossed pattern is sunk into the surface of the material and, depending on the thickness of the material, might protrude on the reverse side. In Figure 10, debossing is simulated for wood and wax to illustrate the change in shape due to material. In the case of wood (top), a series of debossing actions on a straight line is simulated. In the case of wax (bottom), a single action is focused to better show the material deformation. The same tool, contact angle, and force are used in both conditions.

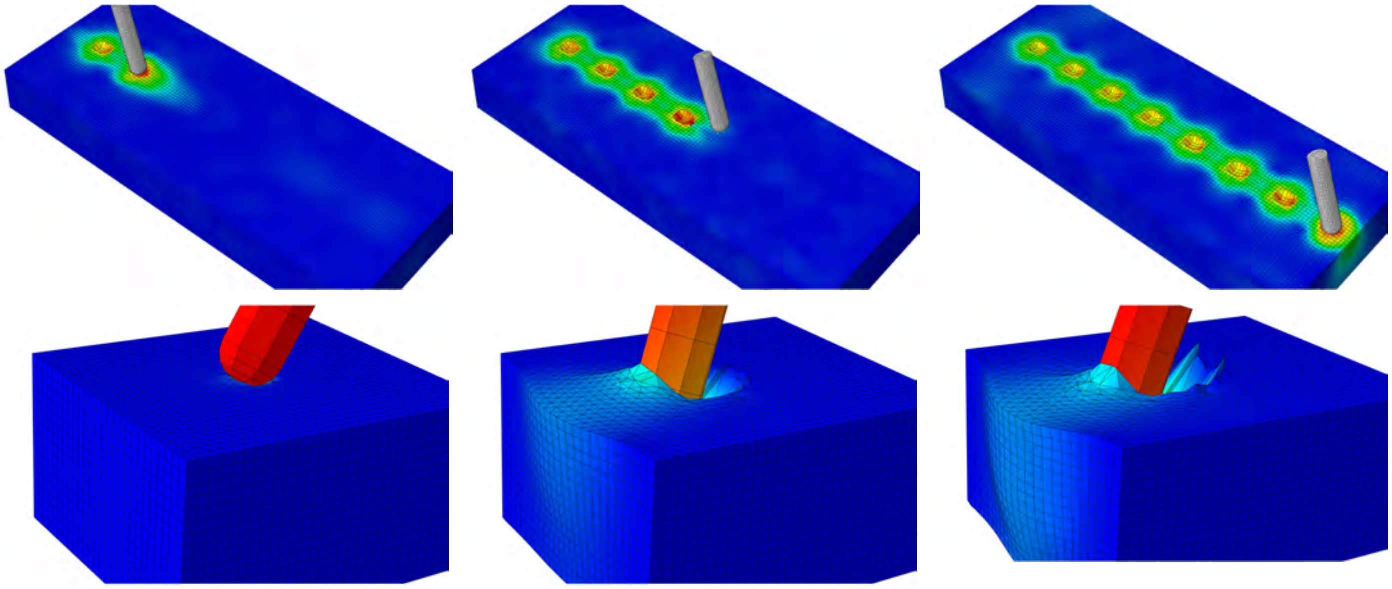

Figure 10. Simulation of repeated debossing strokes that imprint a linear pattern on a piece of wood (**top**) and a single stroke with the same tool in wax (**bottom**).

5.4.2. Bending

In bending, pressure is applied to elongated workpieces to change their shape without breaking them. Bending is afforded by the lever simple machine. The simplest case requires three points of pressure. Depending on the material, care must be taken to avoid breaking the workpiece. Multiple points of pressure can be used for spreading out pressure across the material. An example is simulated in Figure 11, indicating the way that a workpiece is bent. The workpiece is a compact ply of material. The same force is exerted using a round tool.

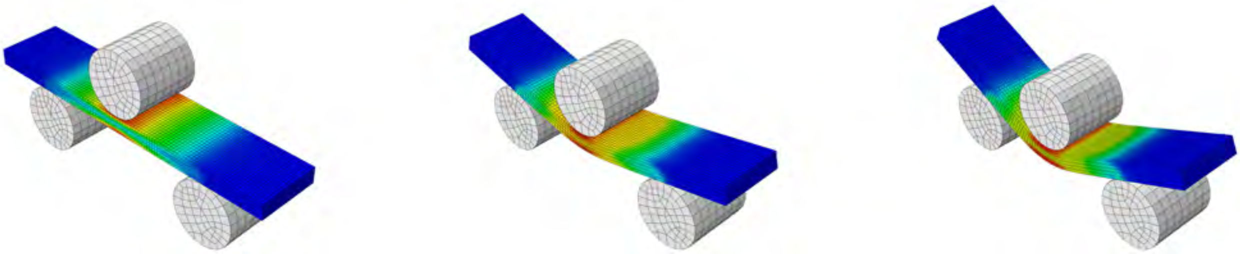

Figure 11. Simulation of bending a ply of material.

5.4.3. Twisting

Twisting applies torsional stress to deform a solid object by rotating it about an axis that passes through it. The relevant material physical properties are plasticity and elasticity because they determine how easily the material will be shaped. Twisting increases the mechanical stress and tension inside the material. If a material is overly twisted, it may exhibit damage.

In Figure 12, the twisting of a ply is studied. Twisting is induced by a circular actuator on the right and by stabilising the other end of the material. 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).

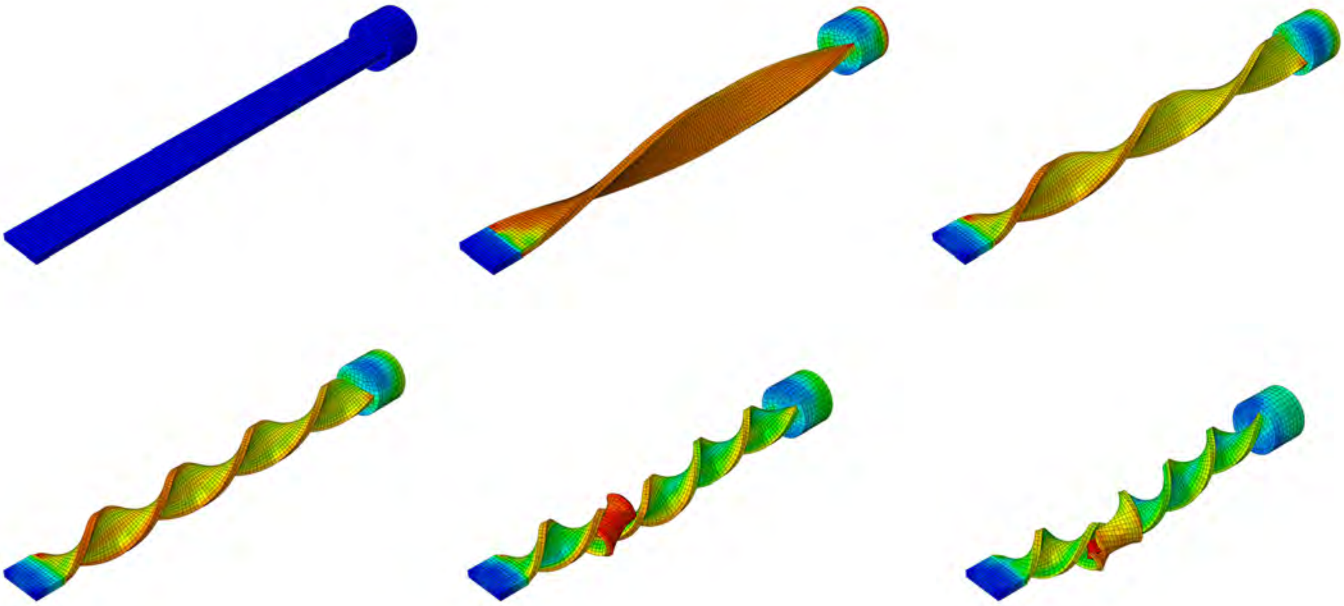

Figure 12. Simulation of twisting a ply of material by stabilising its left end and rotating eight times its right end, eventually distorting the material.

5.4.4. Hot-Rolling

Hot-rolling forms the heated metal into long sheets or rods and is afforded by material ductility. The material, typically metal, is passed between dual rollers revolving in opposite directions. The metal is heated to increase its plasticity but not so much as to liquidate and become cohesive. In the simulation, the rollers are rigid and their activity is modelled as constant rotational motion. Friction is the agent of workpiece propagation through the rollers. The action is iteratively applied to thin a ply of material progressively without damaging the piece or the machine by excessive stress. Each time, rollers are brought closer, and the result of a roll becomes input to the succeeding roll. This is shown in Figure 13 for two consecutive rolls.

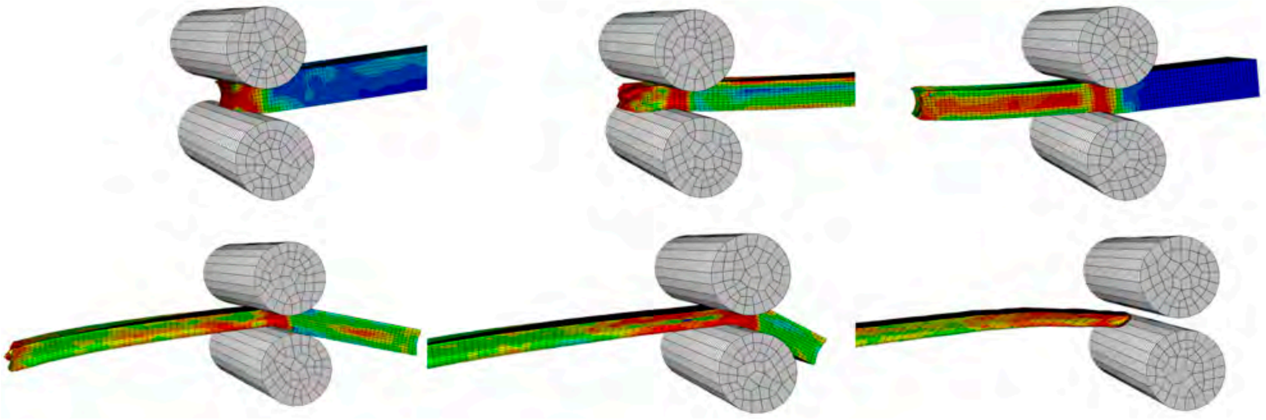

Figure 13. Simulation of hot-rolling process for metal sheets, in two passes. The first pass is shown in the top row and the second pass is shown in the bottom.

5.4.5. Throwing

Throwing is a pottery technique that is similar to turning, but the material is rotated using a potter's wheel. In contrast to turning, the material is not subtracted but formed into a new shape. The simulation in Figure 14 shows a basic pottery action where the rotated clay is pressured from the top to "open" the workpiece and create a hollowing. The practitioner's hand is simulated to apply pressure gradually at the top of the workpiece as it is rotating.

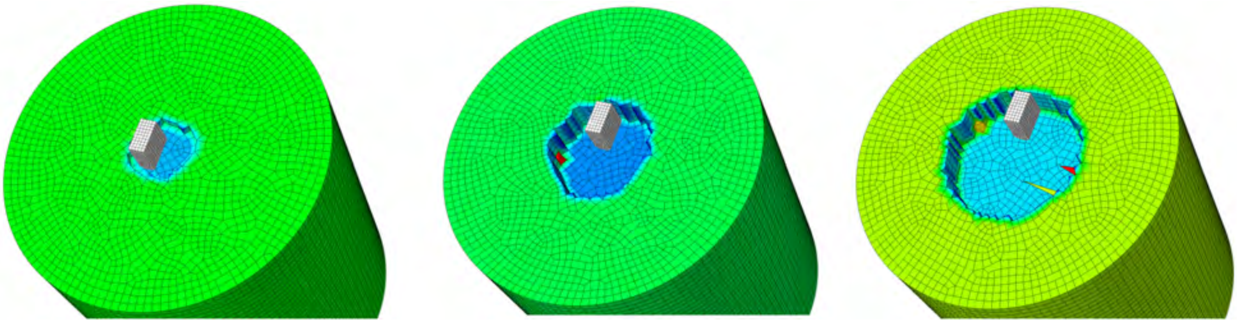

Figure 14. Simulation of clay throwing process for pottery.

5.5. Interlocking

5.5.1. Fastening

Fastening regards the firm and secure interlocking of components, brought by nails, bolts, screws, staples, and pins, that connect two or more parts longitudinally. The case of a nail driven in a workpiece is simulated. The workpiece is made of wood and rests on the ground plane. The nail is made of steel and perpendicular to the surface. After the nail is driven, the opposite force is applied to the nail. As a result, the workpiece is pulled back, lifting the workpiece and indicating the rigidity of the assembly due to the friction and tension between the two components. In this case, the simulation uses a brief pressure force on the back of the nail. The result is in shown Figure 15.

To increase the realism of the simulation template, in Figure 16, we consider the use of a striking tool. The reason is that in practice it is impossible to drive a nail in a workpiece without lateral supporting forces that hold the nail in place during its hammering and which are typically afforded by the fingers of the practitioner. The example below illustrates this by comparing driving a nail by striking with a hammer in two conditions. In condition 1, there are no lateral supporting forces and thus the nail is displaced due to gravity and, eventually, not properly driven into the workpiece. In condition 2, the fingers of the practitioner are simulated by a cylinder applying lateral pressure to the nail and properly driving it to the workpiece.

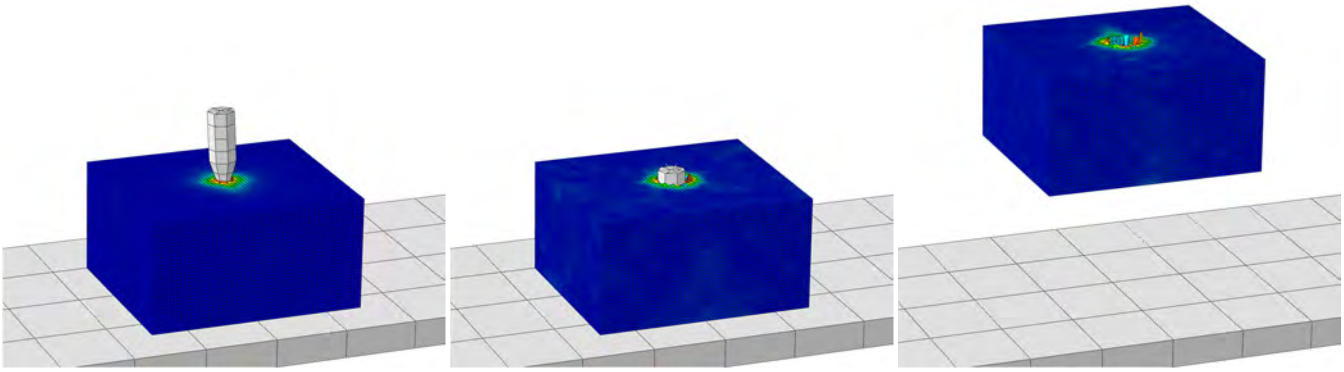

Figure 15. Simulation of fastening with a nail in a wooden workpiece. **Left**: the wooden workpiece rests on the ground plane with the steel nail positioned perpendicularly to its surface. **Middle**: the nail is driven in the workpiece. **Right**: The nail is pulled back, lifting the workpiece.

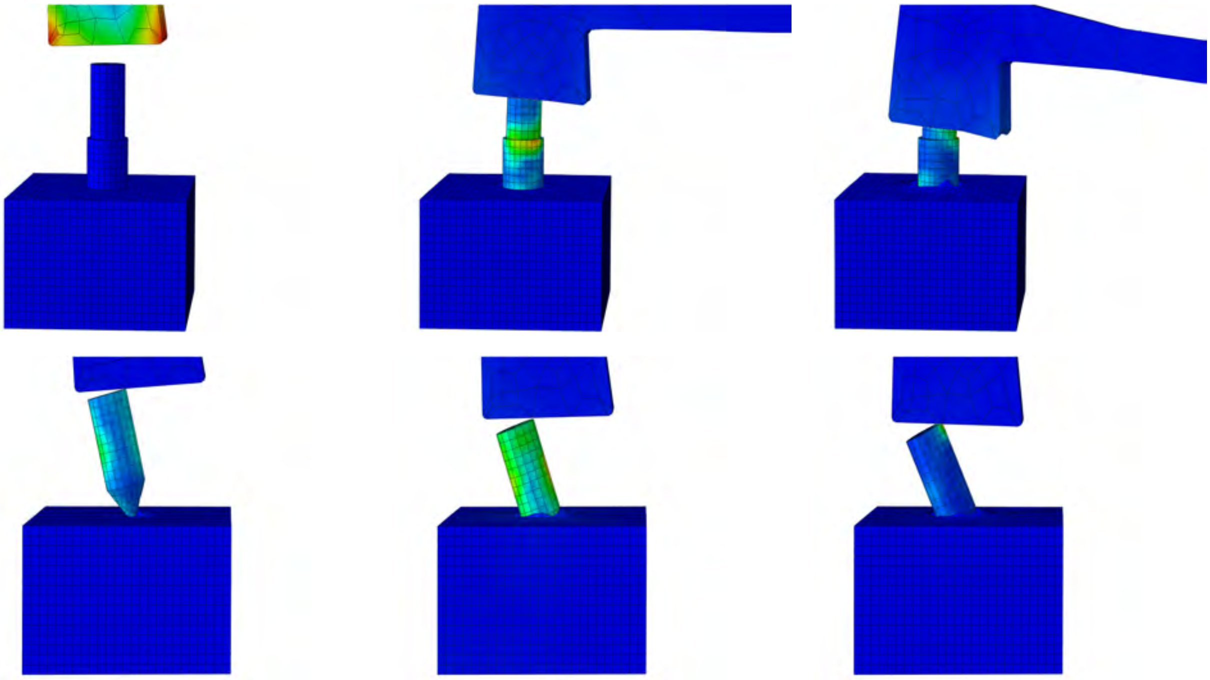

Figure 16. Simulation of driving a nail with and without lateral support.

5.5.2. Swivelling

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. The simple machine that governs this mechanism is the wheel and axle. The term swivel implies the ability of connected parts to rotate around said axle. 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. The simulation in Figure 17 shows the effect of a tight interlocking of swivel components against a loose one. In the first case (top), swivel components are tightly interlocked and stay in place despite the effect of gravity. In the second (bottom), a similar configuration is used but the connections are loosely tight and, as a result, the parts swivel due to gravity.

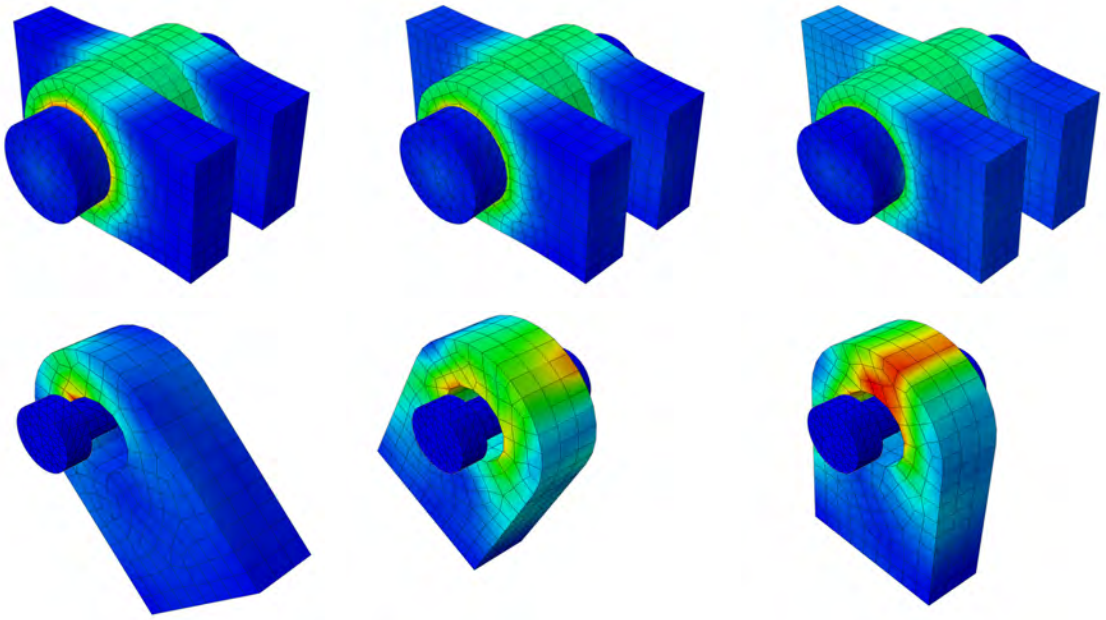

Figure 17. Simulation of swivelling mechanism with tight (**top**) and loose (**bottom**) interlocking.

5.5.3. Weaving

Weaving is based on the interlocking of threads or plies, for fabrics and wicker, respectively. The kinematic simulation using FEM has been extensively covered in [111,112]. More generally, the FEM simulation of elastic knots used in knitting is covered in [43]. In this work, we focus on the structural composition of fabrics and wicker. For this purpose, the TexGen simulator, version 3.13.1, [53] 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 outputs can be imported into the FEM simulator, to predict mechanical properties of fabrics, such as sensitivity to stretching, point of rupture, etc. In Figure 18, we provide examples of textile composition using TexGen.

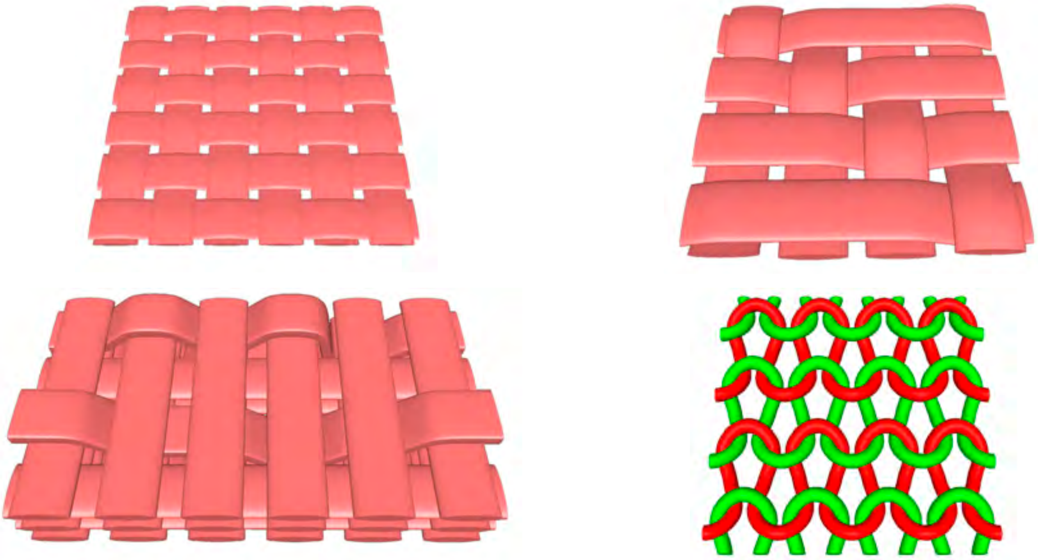

Figure 18. Three weaved and a knit fabric structure created using TexGen. **Top-left**: plain-weave; **Top-right**: satin-weave; **Bottom-left**: arbitrary weave for creating patterned textiles; **Bottom-right**: knitted structure.

5.5.4. Spinning

The techniques for creating ropes and threads from fibres or filaments are called braiding and spinning, respectively. Two or more strands are intertwined by twisting them together while being pulled to create tension that secures the result. The simulation in Figure 19 illustrates the simplest case, where two strands of cotton are pulled in opposite directions from their edges. At the same time, they are twisted in opposite directions. Two rigid tools at the end of the workpieces play the role of practitioner hands, providing the pulling forces and rotational movement.

Figure 19. Simulation of thread twisting for braiding and spinning.

5.6. Interactivity

The results of simulations can be used to create interactive educational applications for specific actions. As simulations are not real-time, simulations can be run in batches by modulating parameters. During the interaction, the appropriate result is looked up and shown.

The carving action was simulated multiple times, modulating the incidence angle and lateral rotation, quantised in steps of one degree. An application was built using the Unity game engine that prompts the user to perform a carving action by controlling the incidence posture of the carving tool. As the user controls the tool, the application selects the appropriate simulation result. Results for three such postures are shown in Figure 20.

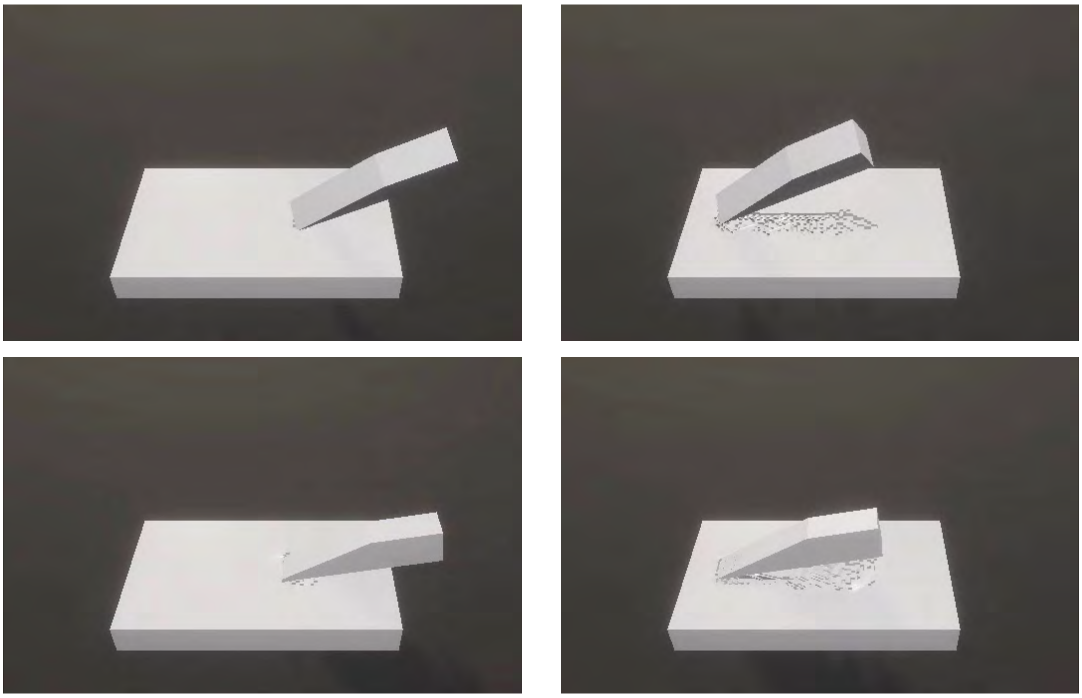

Figure 20. *Cont.*

Figure 20. An interactive application that uses the results of carving simulations for training.

6. Conclusions

This work focuses on modelling the mechanical components of crafting actions and validating these models through FEM-based simulations. A mechanical and semantic classification of crafting actions was presented, in which the basic mechanical components, material properties, tools, and conditions required for the successful execution of each action class were identified.

This identification is utilised to select the computational and material models relevant to the simulation of each action type. In turn, this selection simplifies the development of action simulation archetypes, as refinable templates for the simulation of specific actions of this class. This association extends the craft representations by adding a model of the mechanic principle and parameters that govern craft actions, along with their verbal and audiovisual descriptions. This theoretical contribution is validated through indicative examples and materials, with simulations demonstrating that the proposed classification yields classes that can also be hierarchically structured, indicating the similarity and utility of the templates.

We found that using the proposed framework, flexible simulation templates were effectively specialised to model crafting actions. The simulations demonstrate the versatility of the archetypes across different materials and conditions. Another finding from this analysis is that tools and actions serving similar mechanical functions also share analogous semantic characterisations.

Future research will focus on understanding the role of sensory feedback—such as visual, audio, and haptic stimuli—in practitioner judgements and the modelling of the corresponding mental actions. Additionally, finding ways to integrate expert knowledge will refine our models, capturing the aspects of skill and dexterity and improving the effectiveness of simulation-based learning. Moreover, we warrant ways to simplify the computational load by utilising parallel computation methods, such as [26], to provide more complex and more realistic simulations. Finally, the rendering of simulations with photorealistic realism would increase the aesthetics of interactive demonstrations and make interactive applications more appealing to craft apprentices.

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Appendix A

The names of the traditional craft actions and action classes mentioned earlier are provided in conjunction with their reference ids in the Getty Arts and Architecture Thesaurus in the table below.

Table A1. Association of action names with their IDs in the Getty Arts and Architecture Thesaurus.

Action	ID
Additive and joining processes and techniques	300229467
Bending	300053101
Braiding	300053638
Carving	300053149
Cutting	300053069
Debossing	300265527
Drilling	300053151
Engraving	300053829
Fastening	300053015
Forming	300053098
Hot-rolling	300137949
Incising	300053847
Incising, Splitting, Drilling, and Tearing	300229471
Interlocking	300229467
Knitting	300053634
Metal assembling	300053948
Moulding	300053134
Moving	300263062
Soldering	300053949
Spinning	300053661
Splitting	300263219
Subtractive processes and techniques	300229471
Swivelling	300434215
Tearing	300252881
Throwing	300053908
Turning	300053158
Twisting	300072926
Waiting	300386082
Weaving	300053642
Weight	300056240
Welding	300053958

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