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Abstract: A roadmap is proposed that defines a systematic approach for craft preservation and its evaluation. The proposed roadmap aims at deepening craft understanding, so blueprints of appropriate tools that support craft documentation, education, and training can be designed while achieving preservation through the stimulation and diversification of practitioner income. A roadmap is required because understanding making activities that include *"care, judgement, and dexterity"* [1] call for interdisciplinary contributions from Anthropology, Cognitive Science, Art History, as well as Physical and Computational Sciences, to cover the multifaceted expression of crafts as living and developing heritage, as a source of income, and as the expression of the mind through *"imagery, technology, and sedimented knowledge"* [2]. In addition to this roadmap, an evaluation strategy is proposed to validate the efficacy of the developed results and provide a benchmark for the efficacy of craft preservation approaches. The proposed contribution aims at the catalysation of craft education and training with digital aids, widening access and engagement to crafts, economising learning, increasing exercisability, and relaxing remoteness constraints in craft learning.

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1. Introduction

A roadmap towards the understanding and digital documentation of crafting actions and activities is proposed. The problem is challenging due to the multifaceted nature of crafts, which covers a wide range of both tangible and intangible dimensions [3]. The proposed roadmap recommends ways towards the documentation and sustainable preservation of crafting techniques. Motivation stems from the declining numbers of craft practitioners and apprentices [4] due to a lack of awareness, difficulties in knowledge transmission, and economic demotivation due to the lack of certificates and accreditation of qualifications [5].

Craft refers to the practice of making things using hands and tools. It involves the use of techniques, tools, and materials to produce objects, often with a high level of skill and attention to detail. Craft products that are produced in small quantities, emphasising the individuality and uniqueness of each piece. Pye [1], defined as *"work of certainty"* the predetermined actions outside the control of the operative, and the "work of risk" that which regards actions that depend on practitioner care, judgement, and dexterity. Tools of certainty are moulds, hand presses, looms, stabilizing jigs, and measures, while tools of risk are scissors, knitting needles, chisels, paint brushes etc.

Computer-aided craft education and training are proposed to widen access, economize learning, increase exercisability, and relax remoteness constraints in craft learning. The proposed roadmap aims at the catalysation of craft education and training supported through immersivity aids, craft simulators, and advanced, as well as high-end digitization and visualization. These tools are planned to widen access, economize learning, increase exercisability, train attention to safety rules, and relax remoteness constraints in craft tutoring. Immersive interfaces are recommended as central in providing virtual craft experiences due to the practical nature of crafting. As such, the integration of haptics in these experiences is important to train crafting actions and make explicit the tacit knowledge employed in handiwork.

The simulation of crafting workflows is proposed to support material savings, part reuse, and reduction of energy consumption. The purpose of a simulation is to predict the result of new techniques of individualized tasks for part-specific operations. Safety is important for the training of adult practitioners, but even more important for younger ages. Today, entrance to workshops is prohibited for children. On the other hand, skill is better developed when young and, traditionally, craft skills were acquired during apprenticeships, at small ages. Therefore, realistic craft games and toys can interest and provide exercise opportunities with safety, from an early age. Last but not least, a goal of the proposed roadmap target social benefits stem that step from the role of art and culture in our lives. Craft practice is increasingly recognized as a positive influence on personal and communal well-being when used as a vocational, leisure, and social activity [6].

The proposed roadmap stems from the implementation plan of a three-year research project on traditional craft preservation funded by the European Commission under the Horizon Europe Programme called Craeft, named after the old English term that means art, force, and skill. The purpose of this work is threefold. First, to provide an overview of objectives and activities that exhibit the potential in contributing to craft preservation. Second, is that it contributes to policy and decision-making and provides for product authentication and material provenance. Third is to serve as a resource for individuals or organizations interested in craft preservation, by exposing the proposed approach, methodology, and techniques to criticism by the scientific and heritage communities, as well as to avoiding duplication of efforts by other peers.

To achieve the aforementioned goals, literature from multiple relevant disciplines is reviewed in Section 2. Technical, educational, and training recommendations, followed by business and policy proposals towards craft preservation are provided in Section 3. In Section 4, validation and evaluation plans are provided. In Section 5, conclusions and future outlooks are outlined.

2. Related Work

The ambition of this work is to advance the understanding of crafting activities as an intellectual and physical process that employs perceptual imagery, knowledge, and technology. By formalizing this understanding, we wish to better document, study, teach, preserve, and develop crafting skills, transmit this knowledge for posterity, and use it for the prosperity of craft communities.

2.1. Data and Knowledge Collection

In 1990, UNESCO published a data collection guide for data collection for documentation of traditional crafts [7], identifying the essential elements to be recorded: artefacts, materials, tools, and the crafting process. Photographic documentation was deemed necessary to record the practicalities of the crafting process, such as the way to hold a tool and manipulate it. Since then, digital photography and cinematography advanced the state of the art in the documentation of CH. The types of recordings and their individual recording parameters have to be adjusted to the craft of the study. We review the main recording technologies, classified as to their use in the digitization of physical items, events, and documentation.

2.1.1. Data

Physical items are objects that remain static in time. In formal ontology, they are called endurants or continuants, meaning that their observation is the same at any moment in time. In the context of crafts, they are materials, tools, machines, products, information carriers, and sites. Recording of endurants is achieved through photography [8,9] and 3D reconstruction [10]. Comprehensive guides in the photographic recording of CH artefacts and sites are recommended for this purpose [10–21]. Methods for the digitization of challenging materials [22,23] such as transparent objects. In [10], an approach to the full scope of 3D data curation through the collection, processing, archiving, and distribution of multiple modalities is proposed. A special case of endurants is information carriers such as books and manuscripts. Their primary digitization is photographic. Subsequent analysis regards the extraction of their verbal content conventionally through pattern recognition (OCR) as well as more advanced methods targeting manuscripts [24,25].

In the digitization of intangible cultural heritage efforts focused on phenomenological digitization, targeting the recording of kinetic or vocal activities [26–31]. Cinematographic and 3D motion digitization enabled the recording of performing arts in multiple media and formats, exhibiting immersive qualities and interactive experiences [32,33], and similarly for musical content [34]. MoCap and Computer Vision are used to capture articulated human motion in 3D, documenting body motion in dance–and theatre [35,36]. In crafts, motion capture was employed for the investigation of crafting gestures [37].

2.1.2. Knowledge

Verbal reports aim to access the cognitive processes behind actions and can be carried out either on-line, with the reporter talking as they work, or off-line where the reporter comments retrospectively on their performance, often prompted by an audio or video recording [38,39]. Limitations are the articulation of the reporter [40], as the reporter might not talk about what seems obvious to them or they might alter their performance because they are aware they will have to describe it [38].

In [41], it is recommended to create event logs for each recording session, as soon as possible after it. This urgency stems from the degradation of human memory, particularly when introduced to a plethora of events and details. The logs promote immediate reflection and a summary of actions that both assist in later assessment and comprehension. The logs should summarise activities and short-term observations, to create a narrative of the proceedings rather than a complete record. This has two outcomes: (1) an immediate review of the session that would inform the next stage of the research and (2) facilitation of a subsequent review of the material. In [42], it is proposed that logs can help to search the digital records by content using a keyword search in the logs.

Interviews are widely used methods but they are retrospective and dependent on human memory. Unstructured interviews are useful for establishing rapport and an overview of the activity but can result in large quantities of data [38]. Structured interviews, where the same predetermined questions are posed in the same order, provide more manageable data, but require a deep knowledge of the domain and are time-consuming to prepare.

2.2. Ethnography

Ethnography [43] identifies and describes the activities of social groups and their members as "textual reconstructions of reality" [44]. After the advent of digital imaging, the ethnographic study of crafts was modernized by Wood [41] to include digital recordings. Recently it has been applied in workshops, with examples in carpentry [45], glasswork [46], and textile manufacturing [47].

The interaction between the actions of the maker and the type, properties, and individualities of the material is described as a negotiation [48,49] between the maker and the material. It is further identified as one of the reasons for the uniqueness of craft products. From the perspective of material agency, it is argued that craft practice is the result of a negotiation between the material and the maker and that the bodily movements of practice emerge from this dialogical act. In these works. it is recommended to investigate craft processes from a perspective that uncovers how crafting actions occur through bodily movements and material transformations. The emergence of the artefact is studied with a focus on the relationship between the maker, material, and practice. This examination enables an understanding of what happens in each contact moment between the maker and the material.

Short-term ethnography [50] is an alternative to the traditional format that permits a shorter length of fieldwork activity in return for intense engagement between the researcher and their participants. The rich points that make up an ethnographic account need to be actively sought in short-term ethnography. This can be achieved by utilizing the prior construction experiences of the researcher. The researcher enters the field with an emic insight that can be used to seek out events and allows the production of meaningful ethnography from a shorter, more intense fieldwork period, learning much from individual workers before they move on. Engagement extends beyond the onsite interactions through the use of video to record everyday activities, by introducing attention to reflexive ethnographic practice.

A recent craft ethnography method is [45], where it is argued that ethnography has a lot to learn from artisans and advance a vision for an artisan-inspired ethnography. This work investigates what an artisanal ethnography should be like, treats artisans as ethnographic educators, and what should its, tools, goals, and guiding principles.

2.2. Descriptions and Representations

Craft taxonomies are primarily material oriented [6] and, at a secondary level, classify materials by origin. This classification does not facilitate the understanding of crafting actions, as similar actions can be exercised on materials of different classes.

Craft descriptions are available for many crafts and in several formats. For example, weaving instructions for mechanical were introduced in illustrated manuals since the 19th century [51], instructions for glassblowing in the format of a graphic novel (comic) can be found in [52] while, more recently, narrated videos for crafting can be found in several popular video repositories online. A characteristic of this material is that it is oriented to a specific craft and, as such, a generalisable way to produce craft descriptions and instructions is yet to be found, albeit many crafts share similar principles and actions.

Craft descriptions are classified into thin and thick. Thin descriptions are phenomenological observations of behaviour. Thick descriptions, additionally, include explanations of how these behaviours are interpreted by the participating actors. These explanations include descriptions of intention, attention, judgement, and action modulation [53].

The representation of intangible dimensions of traditional crafts as processes were proposed in [54]. In [55] it was proposed that craft representations should include semantic descriptions of crafting plans and processes, associated with recordings of these processes. These approaches use activity diagrams to represent process steps that transform input materials into output products for each step.

2.3. Cognitive Studies

Cognitive studies in this context aim to examine the cognitive processes involved in traditional crafts, such as mental representations, problem-solving strategies, and expertise development. The focus of these studies is the understanding of how craft knowledge is acquired, organised, and transmitted, as well as how individuals acquire and develop expertise. Moreover, cognitive studies focus on revealing the processes underlying skill acquisition, perception, memory, attention, and problem-solving [56–60].

The perception-action circle is a means of identifying the phenomena taking place during an action [61]. The perception–action cycle is the circular flow of information from the environment to sensory structures, to motor structures, back again to the environment, to sensory structures, and so on, during the processing of goal-directed behaviour [45]. The circle is comprised of four iterating stages: perception, prediction, action, and outcome. This conceptualisation has been used to achieve robotic perception and actuation [62–64] and, naturally, it very well applies well to crafting actions. We take good notice that this circle is a conceptual tool and that attention is not passive but active, while also that actions give rise to additional perceptual stimuli. This is because the practitioner engages the world through the interpretation of sensory images and not direct measurements of the world. As such, experiments and observational studies are required to investigate how practitioners perceive and interpret materials, plan and execute motor actions, and engage in problem-solving.

2.4. Simulation

Simulation studies have been used to understand and analyse various aspects of traditional crafts, including their production processes, and material behaviour. These studies aim to gain insights into craftsmanship, improve techniques, and preserve cultural heritage [65]. Focus is placed on modelling material behaviour during crafting actions and the impact of action parameters. These studies also aim in understanding how different tools and techniques affect the final product, optimise material usage, and reduce waste. An important part of the simulation is the prediction of the behaviour of materials under specific action parameters, allowing the optimisation of techniques.

Mechanical simulation is used in industrial manufacturing for the reduction of human effort, energy, and materials. Finite element analysis [66] is the most widely method in mechanical simulations. To solve a problem, finite element methods partition systems into smaller and simpler parts (finite elements). This is achieved by space discretization, usually implemented by a mesh for each object involved. The method results in a system of algebraic equations applied to predict the behaviour of each element.

Craft simulators exist as digital games and are usually simplified as "play the carpenter" types of games for mobile devices. Woodwork Simulator [67] introduces carpentry tools and their function, but does account for action parameters (e.g., force) and material properties. A review of craft simulation in games that includes an assessment of the realism of simulation can be found in [68].

2.5. Training and Design

Vocational training employs digital asset annotation and workspace simulation. The need for visual annotation upon photographic documentation particularly in handicrafts is identified in [69]. Mixed Reality (MR) and Virtual Reality (VR) environments have been used to train professionals in manual tasks. Human motion has been used for workspace design [70]. Avatars have been employed in manual task collaboration [71]. VR is employed in maintenance training [72]. Immersive storytelling has been also proposed for training [73].

Research efforts were focused on introducing innovative design tools to architects [74,75] studying historical design and patterns as a source of inspiration, and craft preservation [76–78]. Traditional crafts in informal intergenerational knowledge transmission often have a specific focus on product type and regulated style. The industry creates novel design elements and styles, which are applied to multiple products, often drawing inspiration from local tradition. Applied Art & Design schools stand in the middle offering traditional and novel technique learning. The core ideas

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implicit within the Bauhaus are reimagined, retrofitting them for the modern age and its challenges [79–82].

2.6. Sustainability

Immersivity and storytelling have been employed in CH engagement to create compelling and memorable experiences including location-based interactive presentations and experiences [83,84]. Some of the attempts include combining 360° video with storytelling [85], using immersivity to present maritime and underwater heritage [86], employing emotions to enhance narrations on CH subjects [87,88], presenting stories that are part of the intangible heritage of a community [89], and simplifying the design of immersive CH presentations [90]. In the same context, other research efforts were focused on the development of virtual guides with an emphasis on realism, emotional sensitivity, and meaningful dialogue [91,92].

Existing work on the sustainability of CH collections and sites was focused on connecting CH collections in sustainable management [93], empowering CHIs with financial strategies [94], assessing the socio-economic impact of digitization of CH goods and services [95], providing business models for inclusive growth [96,97], creating cultural routes, promoting local and sustainable materials, energy-efficient production, attachment of "green" certificates on products, and reduce training cost, energy, and material footprint using immersive technologies and telepresence tutoring.

3. Method

Phenomenological recording (see Section 2.1) is sufficient for the reproduction of content but is not sufficient for understanding the experience of the performed or practitioner. To record this experience, we recommend representing crafting actions rather than only motions. That is to thicken the ethnographic description with entities and quantities found in the mechanical and cognitive domains, as these have been identified in the respective domains of literature and specifically

- Physical and mechanical events, involving motor-induced actions upon the crafting workspace and materials
- Cognitive events involve mental activities for the perception of the environment, predictions upon possible actions, plans, and judgements.

Moreover, visual and semantic documentation is still distant. To better understand and document crafting action we recommend the semantic representation of the aforementioned quantities and entities. We recommend using the MOP infrastructure [55] to document craft instances in steps, associating phenomenological action recordings with verbal descriptions.

3.1. Overview

In the context of this work, actions refer to the processes or acts of doing something related to the creation of a craft product, according to the current situation, intention towards creating a specific product, or aesthetic desire. Actions involve the execution of physical, mental, or verbal activities to achieve a goal. Actions can be conscious or unconscious, and they can be performed by individuals or groups. The movements of hands and body within the context of physical actions are referred to as gestures. In the context of physical actions, action parameters refer to variables that influence them. These parameters provide details about how an action is performed, including properties that affect its execution, such as speed, force, direction, and duration. Crafting actions upon materials are mediated by tools and/or hands. Actions are events [98].

The goals of crafting actions refer to the intended outcomes that practitioners seek to achieve through these actions. Mental imagery is central to goals and enables the visualisation and mental simulation of intended actions and outcomes. It involves mental representations of actions without their physical execution. Goals are encoded in mental imagery, as the result of mental simulation, planning, or prediction.

Action plans refer to sets of organized steps designed to achieve a goal. They outline the actions required to accomplish a goal. These plans provide a structured approach to problem-solving, decision-making, and implementation of action. Moreover, action plans regard hypotheses for the achievement of goals, such as the prescribed conditions on the state and spatial arrangement of materials and tools. Action plans indicate affordances, availed by working spaces, the human body, and tools, as well as agents of, heat, moisture, chemical reaction, or colour pigmentation. Action plans prescribe the mechanism and the parameters of execution. Special plans are made to handle errors.

We refer to the perception-action circle (see Section 2.3) to conceptualise crafting actions. Our interpretation is illustrated in **Figure 1** and is as follows. During a physical action, the practitioner attends to external (sensory) and internal (somatosensory) stimuli that inform the course of the action. Due to action, more stimuli are generated. The practitioner modulates action parameters accordingly. Mental imagery envisages the anticipated sensory imagery, should the goal be achieved. The result is attended in perceptual imagery created by the senses and judged against mental imagery associated with the action goal. After an action, the practitioner compares mental and sensory imagery and updates or reconfirms the action parameters. Upon completion of a process, the practitioner reflects on its course and outcome and may update it.

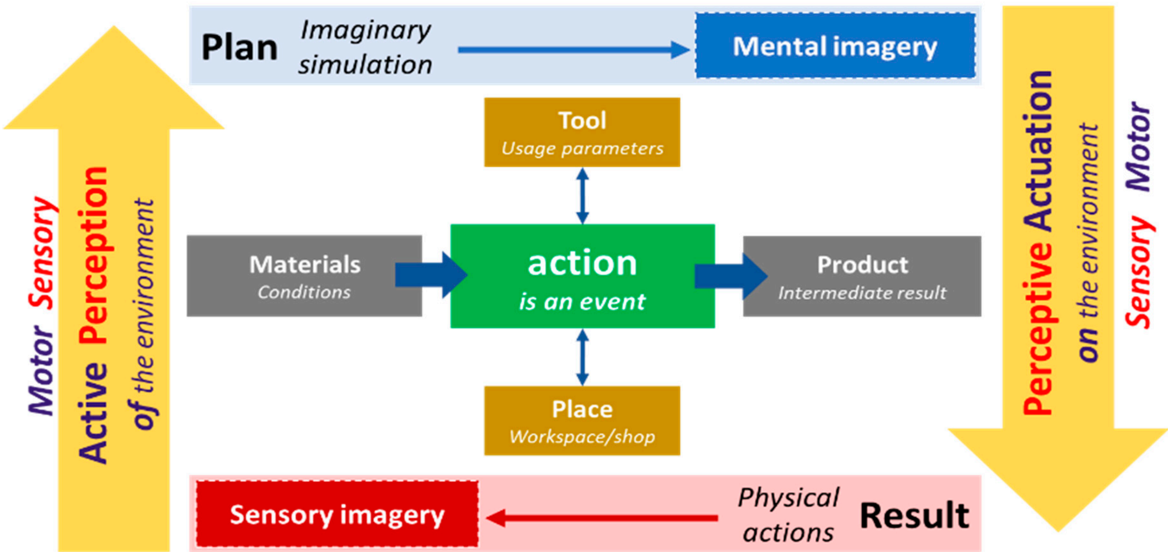

Figure 1. An interpretation of the perception-action circle for the understanding of crafting actions.

A crafting process is defined as the combination of actions in an "umbrella plan" [2] called process schema, or crafting activity. The proposed model brings forward the role of prediction and mental imagery in the formation of action plans. An action model suitable for representing crafts should be able to generate predictions, or otherwise mental imagery [2], which predicts and explains action execution and action results.

3.1. Data Collection

The collection of knowledge on craft practice and the corresponding digitisation tasks require the capture of observations that target the physical, bodily, and intellectual entities involved. The basic means of this type of data and knowledge are verbal and visual records of practitioners, in the form of testimonies and digitisations, respectively (see Section 2.2). This task exhibits interdisciplinary requirements as anthropologists and cognitive scientists are to identify the observations and interviews to describe the aforementioned craft elements in an explanatory fashion, that is to identify and describe sensory, tacit, and intellectual entities. Information scientists will then model these entities as knowledge classes and instances. In addition to the recordings described in Section 2.1, we propose enhancing the recordings with data that foster the generative explanation of:

- Physical properties represent the mechanics of crafting actions upon materials.
- Cognitive properties related to attention and control.

Understanding crafting actions as the negotiation of the maker with the material, calls for the enhancement of data collection with recordings that capture the quantities, properties, and behaviour of objects and materials involved in crafting actions. To achieve this goal the collection of the following data and descriptions is recommended.

3.1.1. Material Properties

Conventional digitization methods for tangible heritage include visual 2D, 2½D, 3D, and 4D digitization of tools, products, and human motion (see Section 2). Digitizing tangible heritage comes with challenges and limitations that need to be considered. These include ensuring accurate measurements, managing data storage and processing demands, and the requirement for specialized equipment and expertise. Exploring these aspects provides a more balanced understanding of the digitization process. Pertinent signals include surfaces, anaglyphs, solids, tool motion, material deformation, sounds, as well as heat, humidity, and other environmental properties.

Material properties are crucial in the conservation and restoration of cultural heritage artefacts. Preservation efforts require a deep understanding of the original material properties to ensure appropriate treatment and maintenance. For instance, understanding how materials are susceptible to environmental factors such as humidity, temperature, or light helps conservators establish proper storage conditions and develop conservation strategies to prevent damage or decay. Material properties contribute to the authenticity and accurate replication of cultural heritage artefacts. When recreating historical objects or traditional crafts, knowledge of the original material properties is essential to achieve faithful reproductions. Thus, the selection of material properties of relevance is craft-dependent. Material properties can be extensive or intensive. Intensive material properties do not depend on the amount of the material and may be mechanical (e.g., brittleness, ductility, hardness, plasticity, viscosity), manufacturing (e.g., castability, machinability), but also acoustical (e.g., absorption, speed of sound, sound reflection), or other. Extensive material properties may include mass, volume, heat capacity, temperature, velocity, tension, and others. Material properties are quantifiable and, thus, can be estimated from measurements or approximated from libraries. Capturing the properties of individual pieces of material and tools enables us to study closer how the same action is instantiated and how the same action is parameterised to cope with the individualities of each piece of material. Dynamic material properties vary over time and refer to the object's motion, material deformation, and modal materials properties, such as stiffness, viscoelasticity, and others. They can be initially approximated from open libraries (e.g., [99]) or measured. To capture the temporal expression of these properties a time-dependent representation is required.

3.1.2. Action Properties

Action properties refer to the parameters of the practitioner's actions, such as grip and body postures, crafting gestures, as well as the motor activity of the practitioner. Typically, these parameters are dynamic because they refer to practitioner motion and action, though sometimes they may remain constant, such as a tool grip. Practitioner motion is captured by vision-based marker systems, vision-based markerless systems and wearables. However, these technologies do not necessarily reveal the amounts of force and effort of the practitioner, we recommend the use of force or tension measurements. This can be directly achieved by pertinent gauges or the use of wearable haptic recorders. Indirectly, they can be estimated through the result of the action on the material, given that pertinent physical properties are provided. Indirect descriptions can be based on data that reveal human effort, such as facial expressions, posture, or even sweat. Training datasets are recommended to associate the semantic representation of actions with the recordings of their material expression (practitioner force and motion, tool manipulation, artefact appearance and geometry, and material transformation, perceptual annotations). The purpose is to bring the semantic and visual representations closer, so that similar examples can be associated but also to create semantically annotated datasets from which the computer can learn action representation.

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3.1.3. Cognitive and Embodied Properties

Capturing and conveying the practitioner's viewpoint call for the identification of the perceptual and action elements of crafting actions. Plans are also entities of interest and include the execution of cognitive actions such as prediction and judgement. Cognitive events are not directly observable and, thus, their digitisation is not simple. Attention to environmental and somatosensory stimuli is an integral part of craft education and training. Environmental stimuli can be recorded in conventional ways, as we can record pertinent events from the environment, using the aforementioned techniques. Environment stimuli can reveal details about crafting actions, such as sound in material processing or inspection. For this reason, data collection should capture environment stimuli that relate to the use of sensory perception in crafting actions. The representation of somatosensory stimuli can lead to the identification of environment events that the practitioner pays attention to. The most challenging entity to capture is sensations and perception because they are "private" and cannot be recorded directly. However, memories of internal signals (qualia) [100] can be verbally testified and recognized out of simulated imagery generated by audio, visual, or haptic rendering. The notion is similar to facial composition software, where by tuning parameters the memory of a face can be synthesized. The particular rendering is, then, a digitization of the sensory imagery the practitioner "feels" [101].

3.2. Understanding

A hybrid, semantic and functional, representation of the recorded crafting activities is proposed. This representation combines the collected data with the semantic interpretation of actions and with mechanical models of their function. The goal is to use semantic annotations, provided by practitioners, to classify craft actions into types of mechanisms and identify environment features and action parameters of relevance. In ethnography, semantic interpretations will be requested from practitioners along with an explanation and identification of the mechanical models to functionally model crafting actions. Making sense of the recordings requires fitting the collected data and representations into interpretations that explain the recorded actions and are by the collected measurements. The interpretations should primarily identify the type of mechanical affordance, the material properties of relevance, and its execution parameters. The latter includes properties such as force, timing, angle of attack, 3D shape, grip posture, and other pertinent properties.

3.2.1. Semantic

The semantic modelling of craft actions is based on a craft-specific ontology obtained by extending the MINGEI ontology [55] with classes and properties needed to model the sensory and mental imagery used in crafting actions. The ontology is implemented on an online platform that extends the MINGEI Platform [55]. The ontology is an extension of the ISO standard CIDOC CRM [102], a vocabulary extensively used for representing CH by the major European GLAMs (Galleries, Libraries, Archives, and Museums). In particular, we reuse some CRM classes and properties for modelling fundamental notions and add our own, as refinements of those in the CRM, for modelling concepts and relationships that are specific to the craft application domain. To increase interoperability, we also use standard terminologies whenever possible. In particular, given its richness, multi-linguicism, and widespread adoption from the CH sector, the Getty thesaurus is adopted [103]. Furthermore, this thesaurus includes a comprehensive collection of action labels. Nevertheless, the platform allows using any other online dictionary or thesaurus, such as the one provided by UNESCO [104] or others provided by national authorities. Thus, a knowledge entity can be associated with multiple meta-data from multiple sources in the proposed implementation.

3.2.2. Functional

To reduce the complexity and enable the scaling of the proposed approach, we recommend creating an ontology able to represent the elementary actions that are common in all crafting actions. Observed actions will be modelled as configurations of elementary ones. The elementary actions are

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identified by the analysis of the mechanisms of interest into simpler, archetypal mechanisms. In particular, actions are classified into Add, Subtract, Interlock, or Transform operations (see **Figure 2**). Materials are correspondingly classified by compatibility with practitioner actions as Free-form (plastic) materials that take any shape, Fibres interlocked into fabrics and Solids that are reduced to a subset of their original volume. A notable subclass of 3D solids is 2D surfaces. Some crafts combine actions and materials of diverse types, as in the crafting of musical instruments.

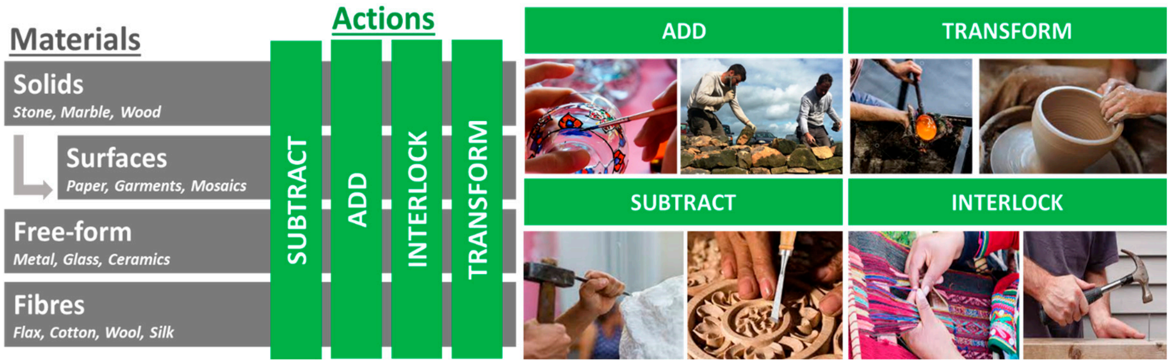

Figure 2. Classification of actions and materials.

We follow the craft ontology [55] to represent knowledge entities for Actions and extend it so that Actions include the tools, materials, and products of each action. Tools are modelled as affordances, to cope with the fact that diverse tools can provide the same functionality and that a single tool also may avail multiple functionalities. For example, a nail can be driven into wood with a hammer or an adz, while pliers can be used to drive a screw or cut a wire. Affordances are modelled as Archimedean simple machines which comprise a small and simple vocabulary that can model all mechanical tools.

As Actions are Events, the representation of the knowledge obtained from recordings of craft practice is used in the instantiation of these entities. The interpretation and analysis of these recordings provide direct input to the instantiated entities, as the analysis of recordings can reveal action parameters used. For example, computer vision algorithms disentangle such properties by learning appearance across modulation of contextual properties. Generation disentangles such properties and encodes material appearance in disentangled space to predict appearance. Existing approaches learn embeddings for 3D objects, mass-preserving transforms from structural constraints (connectivity, stability), texture transfer, and differentiable rendering [105–108].

3.2.3. Cognitive

The term sensory imagery refers to all senses and not solely vision [2]. Practitioners use their senses to acquire information about material properties and events. Mental imagery is the mechanism by which we mentally simulate perceptual experiences and refers to the sensory images of the "mind's eye" (or finger, ear, etc) [2]. Sensory imagery, or qualia, are sensed, e.g., "hand-feel", softness, and smoothness, can be recognised, and recalled as mental imagery, such as when thinking about the colour of amber, the feel of satin, or the timbre of the oboe. Action Plans are formulated as generative hypotheses that can be used to simulate "mental images" of the anticipated results. Their representation of both has a pedagogical value in the training of crafting actions and particularly in the "education of attention" [109].

3.3. Simulation

A way to validate and better understand the crafting is simulation. Simulation has a significant role in both education and training because validating the understanding of a cognitive process is the ability to recreate it [110]. The inclusion of simulation is twofold. The first is to recreate the prediction process or otherwise the practitioner's planning. The second is to use the simulation as an

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educational, training, and design tool. To simplify the implementation, we model actions to be comprised of elementary each one defined by an "archetypal" simulator that implements the action principle. The implementation of each craft-specific simulator will be based on the instantiation of archetypal simulators according to the parameters implementing each case. The simulation result, a realistic virtual artefact, is regarded as simulated mental imagery.

It is important to ensure that the simulated results align with real-world outcomes. Simulating this real-time adaptability and responsiveness can be challenging since the interactions between different materials and their dynamic responses can be complex, especially when considering non-linear material behaviours or variations in material properties.

3.3.1. Archetypal Simulators

Archetypal simulators are to digitally re-enact the basic classes of actions, abstracting mechanics via computational modelling. They will be based on existing mathematical abstractions for the operation principles regarding (1) Add/Subtract by Constructive Solid Geometry, (2) Interlock by Knot/Textile Algebras, and (3) Free-form by mass-preserving, free-form 3D and 2D transforms [111–114]. The archetypal simulators will model mechanical affordances as Archimedean Simple Machines [115] (e.g., a knife is a wedge) or physical & chemical (conditioning) agents i.e., heat, moisture, chemical, etc.

3.3.2. Craft-Specific Simulators

Archetypal simulators will be instantiated into craft-specific simulators, by estimating the relevant range action parameters and predicting the results. Craft-specific simulators will visualize techniques, enable modulation of action parameters, space, and time, offer inventories of tools, and predict the results of the action on the material. An example of a subtractive operation is illustrated in Figure 3.

Figure 3. Similar material subtraction actions across different crafts.

Two approaches will be evaluated for the implementation of refining archetypal into craft-specific simulators. The first is to model physical and mechanical laws, using finite elements. The action parameters and material properties for the instantiation of an archetypal simulator will then be provided from the data collection task (see Section 3.1). The second is to use machine learning to simulate actions from annotated datasets. Generative learning methods, such as Variational Autoencoders and Generative Adversarial Networks [116–119], create novel text, images, and videos, from training data. In crafts, estimators for articulated hand motion for hands that manipulate objects use annotated datasets to create simulators that can be refined with additional data for similar actions on diverse materials [120–122] to realistically decompose and simulate pose, shape, texture, and lighting.

Simulation developers can practice their techniques, experiment with different materials and tools, and refine their skills without the risk of damaging physical objects or wasting resources. They can explore different design possibilities, evaluate material choices, and visualize the outcome of their actions. By digitally recreating the crafting process and understanding the material properties involved, conservationists and restorers can develop appropriate conservation strategies. Simulators can be utilized in the design process to explore different variations and possibilities, aiding in the creation of innovative craft products or techniques.

 doi:10.20944/preprints202306.1214.v1

3.3.3. Implementation

The software that will host the design of simulators will be called Craft Studio and will be used to instantiate craft-specific simulators from archetypal simulators. Craeft Studio will be an authoring platform where action simulators will be combined into process simulators, organizing actions and bringing together partial results, considering fabrication constraints (e.g., order, concurrency, decision points) and spatial constraints of the workshop. In this context, the use of the state-of-the-art for the simulation of dynamic environments incorporates differentiable physics for actions on non-rigid objects and long-horizon tasks [123,124]. Craeft Studio will be used to provide simulation analytics that logs the material quantity used or wasted, energy and time spent. A challenge is the computation of FEMs that could hinder the real-time execution of interactive simulations. However, this can be countered by precomputing results for a range of parameters and invoking the appropriate ones based on user input.

By simulating the behaviour of materials and structures, developers can identify areas of potential weakness, inefficiency, or excessive material usage. Simulation developers and analysts can make informed decisions about the most suitable materials that meet their requirements while minimizing waste and maximizing efficiency. Simulation developers can identify areas where material waste occurs or where process inefficiencies exist.

3.4. Education

Craft education regards theoretical craft knowledge, which includes tool inventories, material conditions and properties, material preparation recipes and, in general, the knowledge that can be acquired by verbal communication. Simulation environments will be used to create educational courses with e-learning capabilities. These courses will introduce vocabulary, material treatment, workspace configuration, measurement tools and, ultimately, crafting processes. The association of semantic annotations with digital assets will be used to generate verbal descriptions and instructions that are illustrated with visual examples. The purpose of 3D and immersive illustration is to place focus on "skilled monitoring", or otherwise *"the ability to evaluate changes brought by practitioner actions and decide if they conform to images of how the work should look at any given stage of production"* [1]. The motivation is to develop critical thinking and judgment on treating craft as a problem-solving process, covered by principles of continuous design [125]. Educational material will acknowledge mistakes and uncertainty as part of skill development. Specifically, commonly occurring errors and their handling shall be included in this material.

"*Declining numbers of practitioners and apprentices*" [1] are due to a lack of awareness, difficulties in knowledge transmission, and economic demotivation due to a "*lack of certificates and accreditation of qualifications, particularly for high-quality training and standards of practise*" [5]. Certification and skill acknowledgement educational programs will be aided by the adoption of digital aids in knowledge transmission. To acknowledge educational and training experience we recommend using the Proof of Attendance Protocol [126] a standard by which projects can award personal ("soulbound") badges that represent participation in events with a role (e.g., student, instructor).

3.5. Training

Mastery, tacit or embodied, knowledge [127], and perception are recognized as the skill to *"move work as quickly as possible with a minimum of physical errors"* [2]. The way people master skills is through repeated practice. Central to the development of dexterity, are the experience of performing motor actions and learning interpretations of stimuli. The main interface for training exercises will be an immersive software environment called "Apprentice Studio". The Apprentice Studio will provide experiences that comprise craft-specific interactive educational materials. Visual immersive interfaces will include AR and VR. Various haptic feedback actuators will simulate the sensations created from the interaction of tools with materials across combinations of physical and virtual instantiations. The system will economize the development of monitoring and action skills, by enabling (a) practice away from the workshop (b) repeated practice on virtual materials (c) immersive

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telepresence of the instructor. Immersion will be used for safety training before visiting the workshop.

3.5.1. Action

The Apprentice Studio will support exercises of crafting actions along with the provision of feedback. Training regards the development of dexterous manipulation for tools of risk. In handwork, tactile interaction is essential to achieve realistic and beneficial training experiences for training. To increase the immersion, realism and efficacy of actions the environment will support haptic interfaces, in addition to conventional 3D multimedia and XR interfaces. This environment will support the training of action, coordination, and synchronization, through opportunities for repeated practice, particularly for free-hand operations. A basic component shall be the training on efficient and ergonomic handling of tools prescribed in these exercises. For this purpose, prior knowledge provided by literature will be incorporated for hand-driven tools [128]. To provide haptic interfaces for design tools to capture the delicacy of human touch and increase design possibilities but also prepare for the actions to take place in the workshop. Will use Craft Studio as an audio, visual, and haptic rendering engine to develop a 3D virtual workspace for the design, manufacturing, and presentation of artefacts. Furthermore, it will integrate craft-specific 3D editing tools that will mimic actions on virtual materials.

3.5.2. Perception

Training attention regards learning to detect and attend to perceptual stimuli and interpret their meaning in the monitoring and control of the action at hand. These stimuli can be (a) external (e.g., audio/video), signifying material qualities, properties, and events, or (b) internal (e.g., proprioceptive, tactile), on awareness of hand & body posture, modulation of applied force/tension, incidence angle, etc. Haptic rendering will simulate inspective tactile sensing and feedback using simple hardware [129]. As bimanual coordination is crucial in the majority of tasks, we will draw ideas from bimanual haptic controllers. We propose the combination of haptics with immersive environments to introduce the affordances provided by hands and tools and their degrees of freedom and guide students through action variability on different pieces of material.

3.5.3. Time

Time awareness is central in many crafts due to the change of material properties over time (e.g., blacksmiths and glassblowers “think hot” as material viscosity decreases as it cools). Simulators will operate in real-time but can be retarded or accelerated for training purposes. Stress destabilizes the learning process [130] and, thus, training simulators will “slow down the time” to ease the practical challenge, similar to music where practice initiates with a slow tempo. Finally, social interaction in the workshop is important for knowledge transmission. Craft materiality imposes a need for co-presence to teach the interpretation of stimuli. Communication is important because part of this knowledge is tacit and understood by the common stimuli shared by the instructor and apprentice.

3.5. Development

To support the design process of craft products, an authoring environment that enables the design of crafting workflows, the testing of new ideas, and the fabrication of material aids is proposed. The software that will implement this is called Design Studio and will employ computer-aided digital design and fabrication. The goal is to conserve practitioner time and to reduce energy and material consumption, through the development of workflows and designs. In this context, we recall that the design and fabrication processes are interwoven and, thus, the Design Studio will support practitioners in exploring workflows that lead to the fabrications of an incepted or given design.

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3.5.1. Design and Workflow

The Design Studio will implement a "sketchbook" metaphor to support the creative process. The Design Studio will employ computer-aided design for the development and testing of new ideas, techniques, and styles. This functionality will reduce experimentation costs, as it will include visualisation of the results predicted by a given action or process, using the simulators of the Craft Studio. The design process will be further assisted through the provision of craft-specific conventional design templates as well as style transfer [131] that may stimulate inspiration. Workflow implementation in the Design Studio will emphasize the fact that often craft products are comprised of parts and pieces. This is important for the functional preview of designs as well as for the study and optimisation of the crafting workflow. The goal is to improve the functional preview of craft products.

3.5.2. Digital Fabrication

The Design Studio will incorporate design tools and drivers for digital fabrication. The purpose is threefold. First to provide the capacity of creating fabrication aids. Second, automate the fabrication of craft artefact parts that are simple to "print". Third, to explore possibilities of hybrid artefacts, e.g., [132]. To achieve this, the Design Studio will interface with additive and subtractive manufacturing protocols and formats, so that 3D models can be directly printed.

To achieve a realistic preview the interaction of artefacts with lighting will be simulation using conventional computer graphics methods. Moreover, a True-AR infrastructure is recommended so that the predicted artefact appearance can account for the environment of the client.

3.6. Preservation

Craft preservation means the continuation of practice and, thus, the existence of motives to do so. The main motivator for producers of craft products is the increase in their income. We propose several ways to increase practitioner income through the divarication of their income streams.

3.6.1. Digital Dimensions

Linking craft products with online content increases, or "digital dimensions", their value. These shall include the following. Creator signage and certificates of compliance with material composition naming and production principles, indicating aspects of design uniqueness, authenticity, and cultural heritage that they express, as craft products embody the cultural heritage, traditions, and stories of a particular region or community. Certificates of compliance with protection indicators, manufacturing legislation and regulations, as well as "green" certificates of production, material provenance, use of sustainable and ethical practices, incorporating eco-friendly materials, and use of fair-trade practices [133]. Moreover, contextualization content in the form of narratives, will be provided to support storytelling about the product, its maker, the materials used, or the cultural significance. We recommend two ways to achieve this implementation. The first is through conventional means, such as barcodes or QR codes in the form of stickers glued on the product. The second is through visual recognition, either of the artefact's appearance or any type of signature or identifier inscribed by the creator upon the product.

3.6.2. New Products

Digital games and physical toys are recommended for the support of craft introduction, recreation, and the development of crafting capacities. Educational toys can be accompanied by instructions, in paper or electronic formats. Combined with online courses, they can cultivate creativity and transmit the values of care, judgment, and dexterity, as well as local traditions for students and cultural visitors. Toys will be designed and developed in Design Studio either simplified for younger audiences or designed to engage creative activities for elders. The digital blueprints of these toys can be marketed in printable formats as electronic products. Digital games can be created by reusing craft-specific simulators to create simplified or serious games, in the realm of electronic creation and design. Digital creations will be encoded in formats importable in common virtual worlds and metaverses used by both youngsters and adults. A benefit of such products is the simplified, and 'safetified' introductory content enabling the training of practitioners before entering the workshop.

3.6.3. Tutoring

Craft tutoring supports practitioner income. We recommend the appropriation of conventional teleconference but also immersive telepresence to support tutoring services. In addition, the recording of workshops and masterclasses can be streamlined by authoring tools for educational material and skill development media, compatible with hybrid participation [134]. This will be a valuable addition to "how-to" instructions and designs from dedicated SoMe, video repositories, and illustrated instruction repositories, e.g., [135], for creative recreation and to improve skills.

3.6.4. Recreation

Reward and motivation play crucial roles in crafting. Reward refers to the positive outcomes or incentives associated with completing a particular task or achieving a specific goal. Motivation refers to the driving force behind crafting. The following aspects are recommended to be addressed in applications targeting craft preservation.

Crafting activities can be driven by intrinsic and extrinsic motivation. Intrinsic motivation comes from internal factors, such as personal enjoyment, creativity, and a sense of accomplishment. Extrinsic motivation stems from external factors like recognition, praise, or tangible rewards. As crafting activities are guided by goals, setting clear and achievable goals provides a sense of direction and purpose, enhancing motivation. Additionally, analysing larger crafting projects into smaller, manageable tasks with specific milestones creates a sense of progress and accomplishment along the way, acting as intrinsic rewards that fuel motivation.

Regular feedback is essential for maintaining motivation during the crafting process. Feedback can come from personal evaluation, constructive criticism from others, or even the tangible results of crafting efforts. Positive feedback or visible progress acts as a reward, reinforcing motivation and encouraging continued engagement in the craft.

Crafting involves learning new skills and techniques. The desire to improve one's skills and achieve mastery in a craft is a motivator. As individuals see their skills progressing, they may experience a sense of accomplishment and intrinsic reward, fuelling their motivation to continue crafting and pushing themselves to new levels. Moreover, crafting can provide social rewards and a sense of belonging. Sharing crafted items with others, receiving compliments or recognition from peers [6], or participating in crafting communities and events enhances motivation and fosters satisfaction.

Reward and motivation intertwine in the elaboration of crafting actions. Rewards, whether intrinsic or extrinsic, help reinforce motivation, while motivation drives individuals to engage in crafting activities, set goals, seek feedback, develop skills, and find satisfaction in the craft.

4. Validation and Evaluation

Ways of validating and evaluating the efficacy of the proposed roadmap are proposed. A set of Representative Craft Instances (RCIs) spanning the range of craft techniques will be used for this task. It is proposed that a collection of such RCIs should include glassmaking and pottery, as representatives of free-form actions, stone and metal sculpting, as representatives of subtractive actions, carpentry and metalsmithing, representatives of additive operations, as well as textiles and tapestry, as representatives of interlocking actions. Comparative studies will regard actions that are employed in similar materials, such as pottery using clay and porcelain, material subtraction in the context of marble sculpting, silversmithing, and woodcarving, or interlocking fibres to create textiles, wicker, or tapestry.

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4.1. Validation

To validate the generality and expressiveness of the approach, three pilots will cover a range of RCIs and compare them across similar techniques and materials employed in their context. The recommended pilots are focused on the following goals.

4.1.1. Preservation

While conservation regards digital documentation in international and open standards for digital libraries, preservation regards the continuation of the practice. The objective of this pilot is to catalyse the continuation of practice through craft education, training, and awareness. Central in craft preservation is the provision of education and training opportunities for new practitioners. This includes formal training programs, apprenticeships, workshops, and mentorship programs where experienced practitioners pass on their skills and knowledge to the next generation. The pilot should provide digital aids that are appropriate for the training programme of RCIs. The enhanced programme will be evaluated at the training programmes of RCIs and improved based on feedback. Validation will assess the efficacy of the developed training materials by measuring the time saved in training and the degree to which these materials assist craft education and training. Moreover, it will measure the interest in remote tutoring and technical assistance.

4.1.2. Valorisation

Product valorisation regards the increase of product value for the customer and the reduction of cost for the practitioner. The increase in product value will measure the practitioner income created by craft products enhanced with digital dimensions, and new products, as well as income created by computer-aided tutoring. Reduction of production cost will measure material energy savings due to the development of efficient workflows, reduction of tutoring cost, gains from refurbishment and remanufacture, and new designs that reuse parts for a circular economy.

4.1.3. Craft Development and Revival

The development and revival of crafting and design skills regard learning from traditional techniques, reusing design inventories, use of traditional techniques in contemporary products, and the reduction of experimentation costs. The objective is to revive traditional techniques and develop novel designs and fabrication possibilities. As such, craft-specific digital design and fabrication aids that help the acquisition of insight from the exploration of new designs and aid contemporary product making, as well as new materials and fabrication possibilities are central. The pilot will measure preview realism, fabricated aids, traditional techniques utilized and savings due to the reduction of experimentation time and cost.

4.2. Evaluation

Since the contribution of the proposed work regards the generality of the approach, the primary evaluation will address the degree to which the full range of crafts and materials is successfully applied. The assessment will evaluate the number of curricula and the degree to which digitally enhanced craft education and training are employed, for the proposed approach to all RCIs

In terms of preservation, it is proposed assessment to evaluate how income streams are increased and diversified due to computer-aided tutoring, design, and fabrication, as well as the penetration of products in diverse markets. It is recommended to measure the crafting actions represented, the craft-specific simulators developed, the fabrication aids implemented, and the artefacts enhanced with digital dimensions.

To assess how the proposed approach motivates craft continuation and preservation, it is proposed to evaluate the response to requests for tutoring, as well as the market demands for products that blend tradition with contemporary needs from utilitarian items. Thus, the assessment is to measure the number of digitally enhanced education and training aids rendering learning of crafts more accessible, effective, and affordable.

The assessment of craft products valorisation is proposed to be assessed by the digital dimensions of craft products through online content and certificates, the games and toys developed, as well as the products which serve personal expression, wellness, and recreation. In terms of cost reduction, it is proposed to measure the number of workflows that save materials and conserve energy, as well as, the reduction of training and testing of techniques in simulation before the workshop. Moreover, it is proposed to measure the economic impact, by assessing any increase in market demand, improved income opportunities, and the development of sustainable craft-based enterprises. Economic indicators regard revenue generation, employment rates, and market growth.

The sustainability of the proposed approach regards relationships and networks between research and heritage sites, cultural and creative sectors, universities, research institutions, regional/national authorities, and enterprises relevant to innovation and sustainable growth. This impact can be measured by the number of practitioners, creative industries, enterprises and academia interested in the proposed approach. Moreover, the cultural significance can be measured by community engagement, gauged by factors such as increased awareness, participation in preservation activities, and inclusion of craft techniques in cultural events or exhibitions. In this context, it is proposed to measure the number of collaborations and partnerships, due to the proposed approach, collect feedback, and compare with similar initiatives in other regions or countries. At the same time, it's important to gather feedback from users, such as trainees and practitioners. Feedback can help identify areas for improvement and ensure that the tools and resources meet the needs and expectations of the users and perform an evaluation of the knowledge exchange and dissemination efforts associated with the roadmap.

5. Conclusions

The proposed roadmap aims to outline a series of steps, strategies, and interventions necessary to safeguard and revitalize traditional crafts, including documentation, skill development, community engagement, policy advocacy, and integration of crafts into sustainable market channels. Policy recommendations for supporting craft preservation efforts providing financial incentives, fostering market access, and aiding cultural heritage policies and education curricula are provided.

In this context, this work identifies challenges faced in the preservation of crafts and proposes preservation approaches that are generic to the type of craft and material, through the provision of an abstractive and generative approach to the modelling and simulation of crafting actions, as well as ways to motivate the craft practice continuation through the diversification of practitioner income streams, digitally fabricated manufacturing aids, and resource economisation.

Moreover, the importance of long-term sustainability to craft preservation is stressed. This involves considering the environmental, social, and economic dimensions of craft practices. This includes encouraging the use of sustainable materials, fostering cultural entrepreneurship, and creating markets for new craft products and services.

The need for an interdisciplinary approach to craft preservation that leverages interdisciplinary expertise, resources, and perspectives is underscored. This is due to the importance of integrating traditional craft knowledge with contemporary approaches. modern materials, technologies, and design principles to ensure the relevance and viability of crafts in contemporary contexts.

Overall, this work emphasizes the significance of preserving traditional crafts, by recognising their cultural heritage and treating them as economic assets, and knowledge. Thus, the preservation of craft diversity and cultural identity are key for sustainable local economies and, thereby, craft preservation.

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