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TOWARDS AN INFORMATIONAL UPCYCLING: LEVERAGING COMPUTATION TO (RE)DESIGN BIOMATERIALS' LIFE CYCLES

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ABSTRACT

As the imperative to mitigate climate-altering emissions and curb natural resources exploitation intensifies, the fields of architecture and industrial design are compelled to explore alternative material practices. This imperative requires a transition from the traditional cradle-to-grave model to a cradle-to-cradle design paradigm, emphasizing upcycling, the process of repurposing waste into higher-value products. However, the definition of "value" in this context remains vague. In this paper, we posit value as an informational shift, denoting the "ecological intelligence" embedded within recycled materials compared to their prior life cycles. Amidst the concurrent ecological and digital transitions, the concept of "Informational Upcycling" (IU) emerges, bridging Circular Economy principles with the creative potential offered by digital technologies and Artificial Intelligence (AI) in architectural and technological design. IU leverages computational methods to address the complexity, non-linearity, and unpredictability inherent in reclaimed materials, which pose challenges to their reuse and upcycling, thereby questioning established design methodologies and tools. This conceptual framework is informed by a case study analysis of international critical research practices and is articulated through a comprehensive digital workflow, pointing out the enabling technologies for IU, with a specific focus on wood waste. Finally, the paper illustrates the application of this theoretical framework through the FoRWARD (Furniture Waste for Circular Design) research project, funded under MICS – NextGenEU, PE11, Spoke 4. Led by the Department of Architecture at the University of Naples "Federico II", this initiative aims to test this approach within the Italian furniture industry, showcasing practical implementations of IU principles.

1. INTRODUCTION

In many ways we can adjectivize the Age of Transition we are living – ecologic, digital, economic, cultural, social, etc. Despite the specificity of each single topic, the term "entangled" (Oxman, 2016) is probably the one the better expresses the complex nature of the significative environmental, technological and social transformations that are imprinting the ways we reflect about problems and, therefore, define the tool with and through which we take action.

In the field of design, and especially of Technological Design, "transition" has cognitive and technical aspects that represent an identity trait of the Discipline, that has always addressed the integration of the "new industrial means" (Crespi, 1988; Nardi, 2000) towards a sensibility for the intertwined network of links and consequences that the human action establishes with the environment, intended as an eco-socio-technical milieu (Grabowski et al., 2017). Indeed, such transformations are stressing out the established relations between design-process-product, matter-form-tools and, eventually, humans-nature-technology (Perriccioli et al. 2020). Computational Design, Robotic Fabrication or Artificial Intelligence (AI) aren't just a new set of instruments that update, in a digital fashion, the previous (Negropone, 1969); neither they stand "neutral" towards the ways their use has an influence on the design processes and their outcomes (Russo Ermolli, 2020).

In a similar way, the principles of Circular Economy (CE) are questioning the conventional methods of design, thus assuming the aspect of technological drivers more than just indicators and checklists. «A Circular Economy» – the Ellen MacArthur Foundation states (2013) – «is a systemic approach to economic development designed to benefit businesses, society, and the environment. In contrast to the 'take-make-waste' linear model, a circular economy is regenerative by design and aims to gradually decouple growth from the consumption of finite resources».

This study makes an attempt to define a theoretical framework that links CE and Computational Technologies, here assumed to be intertwined, according to a "blue and

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green" paradigm for the Age of Transition (Floridi, 2020; De Wolf et al., 2024). The "cooperation" between circularity and computation is understood as a crucial step towards an "Informational Upcycling" (IU), here defined as the process of transforming or redesign waste into higher value products with an increased information content. IU is a design-driven recycling strategy that leverages computation and digital manufacturing to convey an informational shift in terms of material features, environmental performance and socio-economic sustainability, between a recycled material and its previous life cycle(s).

The conceptual outline of IU is informed by a case study analysis of international critical research practices and is developed in the form of a comprehensive digital workflow considering reuse and recycling strategies. In particular, the study is dedicated to wood waste, being timber one the most widespread material in construction, furniture, packaging etc. and, despite its fame of "sustainable resource", is craving for more rational and effective ways to be recovered (Yu & Fingrut, 2022).

Finally, the paper describes the upcoming application of this theoretical framework introducing the FoRWARD – Furniture Waste for Circular Design research project (MICS – NextGenEU, PE11, Spoke 4), coordinated by the Department of Architecture, University of Naples "Federico II", specifically addressed to test this Technological Design approach within the Made in Italy furniture industry. The FoRWARD research aims at experimenting a sustainability relationship between technological innovation and communities, with the goal of reducing the gap between research and practice experimenting collaborative laboratories in weak territories as a driver for social and economic resilience. Specifically, in this paper the methodology for the design of new materials' life cycles from recovered wood waste through digital enabling technologies is presented, and the future implementations are illustrated.

2. A COMPUTATIONAL FRAMEWORK FOR CIRCULAR ECONOMY

2.1 Circular Economy and Digital Enabling Technologies: policy, insights, challenges

CE and digital tools represent the backbone of the recent EU policy for the goal of a "sustainable built environment" (European Commission, 2015; 2019; 2020). This guidance advocates the adoption of the Key Enabling Technologies (KETs) – BIM, GIS, Virtual and Augmented Reality, Digital Fabrication, Blockchain, Internet of Things, Digital Twins, Artificial Intelligence (Pimponi & Porcari, 2020) – throughout the entire Architecture, Engineering, Construction and Operation (AECO) supply-chain, not only as a tool for improving the efficiency of the management of buildings, but especially in the early stage of the design process (Cays, 2017), whereas the impacts on decision and the expected benefit in terms of life-cycle are higher (Bernstein, 2018).

Nonetheless, among researchers, practitioners, firms and companies the use of KETs for CE is still underconsidered: in a previous study (Rigillo et al. 2023), it has been outlined how the AECO industry is struggling to implement digital processes within its workflows, and the topic of the relationship between circularity and digitalization is still underinvestigated, notwithstanding the efforts the EU put in terms of protocols and legislation.

These results are explained by the different complexities of the KETs, as well as by the rooted distrust of the AECO industry towards technological innovation (Agarwal et al., 2016). This condition seems to be related specifically to the EU context, precisely because of the strict legislations emendated by the Union, while in other areas (USA, Australia, UK, China, etc.), the less constraining nature of the regulatory system appears to have favored technological and design experimentation.

One other impeding factor may lie in the very structure of the EU supply chain, where SMEs are the norm. This negatively influences the industrial development, especially in the AECO. Finally, the analysis underpins three main consequences: low capacity in natural resources and waste management; low ability to create and support supply chains; low education rate in terms of digital culture and awareness (Goran et al., 2017).

2.2 Beyond Technology: a "New Kind of Science" for Circular Economy

Among the abovementioned criticalities, the latter seems to be the most urgent, considering how fast technologies are evolving and changing in time. In this context, McKinsey already pointed out how the cultural preparedness of the AECO operators is essential, beyond the development of technological skills (McKinsey, 2017).

The cultural pervasiveness of digitalization, in fact, has touched every aspect of existence at technical, economic, social levels (Picon, 2020). In architecture and design, the digital tools form an ecosystem of innovative enabling technologies that involve Computational Design, Digital Fabrication, 3D Scan, Artificial Intelligence, etc., changing the way designers communicate and collaborate, analyze and simulate, fabricate and assemble (Tamke, 2019).

Digital technologies are already drawing a "new kind of science" (Wolfram, 2002) while they are enacting "the end of theory" as we know it (Anderson, 2008; Carpo, 2023): in front of growing sets of Big Data, the traditional scientific approaches are completely inadequate if compared to the new, non-linear, abductive and statistical methods of computational technologies. For design and architectural research, this involves a co-evolutionary approach (Attaianese & Rigillo, 2021), both in processes and outcomes, within which the possibility of enucleating design questions in a radically different way and of reducing the informational distances between design and production are redefining the traditional relationships among the different actors involved in the process, as well as between the designer and his/her work.

This assumption is not immune to contradiction: not only for the total absence of semantics within the logics of computational intelligence (Hayles, 1999; Carpo, 2019) that poses serious problems for the un-falsifiability and un-recoverability of the "a-scientific" computational processes; but, indeed, for the only apparently "immaterial" substance of information, thus qualifying as energy intensive and extractive, both in terms of data and resource mining (D'Abbraccio & Facchetti, 2021).

Beyond hopes and fears, towards this "inevitable" change (Kelly, 2017) current research is called to respond to the rising need for theories, more than tools (Russo Ermolli, 2020), asking whether digital technologies can make more sustainable and circular the transformation processes of the built environment.

2.3 Reclaimed resources as a computational material

As the acceleration in every social, economic, environmental and technological dynamic is unstoppably growing (McNeill & Engelke, 2016), the scarcity of resources and the need for reducing energy consumption and material exploitation are pushing to privilege reuse and upcycling over recycling (EMF, 2015) and new challenges are facing Technological Design. Unpredictability, uncertainty and non-linearity describe reclaimed materials' behaviors, performance and availability, hindering or impeding their use in the industries. Designing with recovered resources and their life cycles, indeed, means to be hinged with information and optimization depending on the capacity of available supplies; it also implies to deal with difference and non-standardization, where every piece is unique in size, number and features. As the "production" of reclaimed materials is not informed by the market demand, but happens depending on un-foreseeable circumstances, their stock is limited and heterogenous, thus requiring to be optimized. Being waste an unpredictable and unstable resource, digital technologies can help designers to grasp complex behaviors and anticipate problems, providing for a deeper understanding about materials and design.

In these terms, reclaimed resources can be considered as a computational material, and then requiring for computational, "post-scientific", non-standard and non-linear tools. This approach is not entirely new. Mario Carpo already pointed out how computational practice is very similar to the artisanal one, both sustained by a "trial & error", abductive logic (2017; 2019), not oriented to the general modeling of problems (i.e. like science does), but to "formulate of the specific" (Ahlquist & Menges, 2011). Nonetheless, the growing distance between "stand-alone", state-of-the-art research and widespread design and craft practices poses serious questions and can be identified as an urgent field of reflection (Ryamarczyk, 2020).

3. TOWARDS AN "INFORMATIONAL UPCYCLING": ESTABLISHING A COOPERATION BETWEEN CIRCULARITY AND COMPUTATION

3.1 Questioning the definition of "value" in upcycling

Most recycling involves converting or extracting useful materials from a product and creating a different product or material. Depending on the outcomes, recycling can be distinguished into upcycling and downcycling. Upcycling, also known as creative reuse, is the process of transforming by-products, waste materials, useless, or unwanted products into new materials or products perceived to be of greater quality, such as artistic, use, economic or environmental value. Upcycling is the opposite of downcycling. Downcycling involves converting materials and products into new materials, sometimes of lesser quality (Braungart & McDonough, 2003; 2013).

In both cases, however, the notion of "value" is vague. Being the implementation of upcycling based on the difference between a recycled product and its precedent condition and considering information "a difference which makes a difference" (Bateson, 1973), in this study we address the concept of "value" as an informational shift, i.e. the difference in ecological intelligence – material features, environmental performance and socio-economic sustainability – that a recycled material or product holds compared to its previous life cycle.

We define "Informational Upcycling" (IU) as a circular design strategy aimed at the increase in information content (informatization), to which must correspond the decrease in environmental weight (dematerialization). IU leverages computation and file-to-factory techniques to actualize this informational shift, re-evolving industrial processes and re-organizing waste material properties into more complex informational structures provided with novel designed features and a reduced impact, e.g. in terms of carbon emission expressed in kg of CO_2 eq.

3.2 Informational Upcycling as an "extropic" design strategy

IU is an "extropic" design strategy, i.e. it is oriented at retaining the entropy of materials, processes and products originated by reuse, remanufacturing and recycling activities.

Entropy is a thermodynamic principle that describes how all things inexorably tend to dispel energy into randomness and chaos. Nevertheless, biology contravenes to this law through energetic processes that assemble simple elements into complex structures at multiple scales (Dade-Robertson et al., 2024). According to Kevin Kelly, technology acts in an analogue fashion. Technology (or "Technium") autonomously evolves through sophistication, self-training and data compression from materiality to immateriality, augmenting information and hierarchy to result in complexity and organization. Borrowing from the philosopher Max More, Kelly calls this phenomenon "extropy" (Kelly, 2010).

This definition of "extropy" suits the concept of IU for both organic- and inorganic-derived waste materials. Nevertheless, in this paper we focus on organic materials, as wood, which pose a more problematic questions to be tackled: how can we upcycle waste deriving from informationally complex living entities?

Dade-Robertson et al. pose this question and make a distinction between organic and inorganic manufacturing. Modern fabrication methods involving biologically derived materials are, according to the Authors, unwittingly engaging in an "entropic manufacture": «we spend energy to convert highly structured complex materials into simpler, more disordered materials before using more energy to assemble them into composites across often geographically distributed manufacturing chains. Consider the journey of manufacturing paper. A tree, which is a complex multi-material object - a sophisticated organization of cellulose, hemicellulose, and lignin finely tuned and organized at the microscopic scale to yield functionally graded materials from the trunk to individual leaves - obtains nutrients and energy from its environment, self-assembles, is responsive, and can produce and distribute information for new trees through its seeds. To make paper, we first undergo a series of disassembly steps […]. While paper is functionally more useful for writing a letter than a living tree, this approach, involving building through a process of disassembly, seems counterintuitive» (Dade-Robertson et al., ibidem).

In the case of timber waste, indeed, the most common recycling strategies contemplate entropic manufacturing by downcycling, i.e. recycling to produce low-quality products (such as particle boards) or incineration to generate energy. Particle boards, a common product from wood waste downcycling, hold significative impacts in the transportation, manufacturing and end-of-life stages. Their production involves the use of chemical or bioderived additives. Once disposed, they are further downcycled, landfilled or incinerated. In any case, the "value" of wood gets scattered throughout energy-consuming processes and its life cycle decreased, at a growing environmental cost (Campbell-Johnson et al., 2020). In this way: «[With] our manufacturing methods [we] impose disorder and randomness on our materials. We accelerate entropy to give the illusion of order in our constructed environment» (Dade-Robertson et al., ibidem) (Figure 1).

3.3 Informational Upcycling actualization. Using computation to (re)design material intelligence

To be effectively "extropic", the actualization of IU requires to regeneratively design new ecological intelligence in reuse or recycle processes and products. The result is an informational shift between the recycled product and its previous condition or life cycle, realized by:

1. increasing the information content (i.e. the informational difference between life cycles);
2. reducing the environmental weight (i.e. the environmental difference between life cycles).

Defining actualization as "the process of bringing something into existence", computation is the elective means for the actualization of IU. In the words of Achim Menges, computation is: «The processing of information and interactions between elements which constitute a specific environment. Computation produces outcomes realized from the processing of internal and external properties. It provides a framework for negotiating and influencing the interrelation of datasets of information, with the capacity to generate complex order, form and structures. Computation as a design methodology is to formulate the specific. Computational processes start with elemental properties and generative rules to end with information which derives form as a dynamic system» (Menges & Ahlquist, 2011).

Computation rediscusses the relationship between design, matter and production by introducing information as a "value" in the materialization process. Actualized by computation, IUproduces an informational shift by "evolving" already crafted techniques, objects or materials.

As for biological organisms, Kelly claims that entropic evolution-through-information is an inherent trait of technology itself (Kelly, ibidem). Describing the shift in construction techniques from an artisanal to an industrial economy, we can compare a simple clay brick and a complex ceramic façade component by the difference in the information structure and content (Campioli, 1992). In the first case, we have the lowest level of information: a brick only contains basic "data" about material and dimensions. We have (almost) unlimited range of possibilities – we can build walls, cladding, vaults – exactly because we have no direct instructions from the product or the material itself. As Louis Kahn, we need to ask the brick "what does it want to be", that is, any possibility can only be actualized through design, but design itself only happens after the brick. Shifting into an industrial paradigm, the same material is employed to design, fabricate and assembly a ceramic façade component. Here, we have a higher level of information. Material is shaped by design and so the product contains all the instructions the builder needs to assembly it, provid-

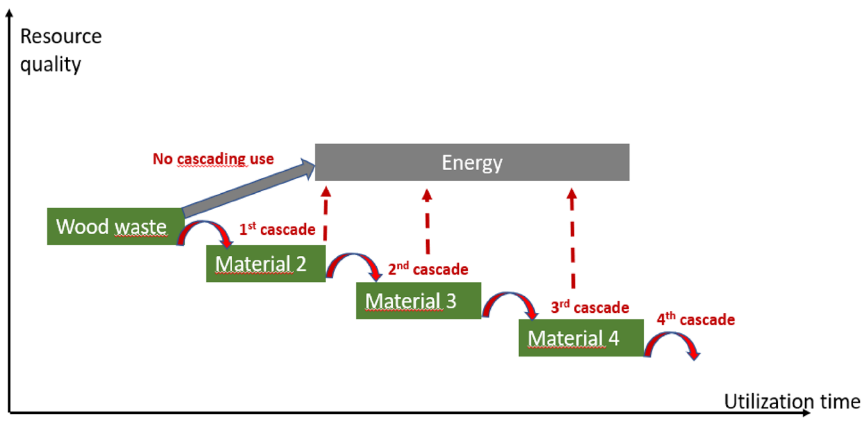

FIGURE 1: Cascading effects of wood waste. Source: https://www.mdpi.com/2073-4360/13/11/1752.

ed by design. Even if standardized, such a component can be specialized to specific uses (for instance, incorporating sun-shading lamellas with a specific orientation depending on the average site conditions) and positioning (e.g. base or top level).

In our post-industrial, file-to-factory manufacturing context, the balance between information and matters tends to a state of poise. Taking a 3D printed clay component, there is no loss of information between matter and design, the shape of the objects is unique and totally derived from the design. The content of information is at its maximum, the shape is optimized and through the process from artisan to industry to digital we get more immaterial content and less material weigh. Indeed, the object is directly shaped to the information of design, and the material can be additivated or modified, i.e. "genetically" modified in shape and very structure for specific, unique design intent.

It is worth noting how information (conveyed as a sum of signals and components) increases from the brick to the façade component. In the 3D printed clay object, however, the number of components decreases again. Dematerialization, just as information, is a consequence of extropy determined by computation.

4. DIGITAL OPPORTUNITIES FOR AN INFORMATIONAL UPCYCLING. AN IN-DEPTH IN THE WOOD INDUSTRY

4.1 Methodology and limitations

In this section, the concept of IU is actualized through a case study analysis of international critical research practices, collected and reviewed to illustrate opportunities and challenges of the theoretical assumptions abovementioned.

The in-depth analysis is dedicated to wood waste: timber is not only one of the most widespread materials used in construction, furniture and packaging, but it is a renewable and carbon storing resource, the use of which is strongly promoted by the EU Green Deal. Nonetheless, there is a scenario of rising demand for wood products (FAO, 2018; Gresham, 2020), that also implies a growing amount of waste will be generated during the construction, refurbishment and demolition phases. Nevertheless, at current state wood waste is usually downcycled or incinerated and used as fossil fuel, thus requiring more efficient ways to be recycled and reused (Beyer et al., 2011; Cazzaniga, 2022) (Figure 2).

The case study collection takes into exam major research centers working with digital enabling technologies for wood waste reclaiming and upcycling. The examples are selected for their representativeness regarding the topics of this dissertation. Further studies and future implementations of this will broaden both the number of case studies and the typologies of debris and materials to be considered.

In the first sub-section, this analysis is developed in the form of a comprehensive digital workflow for the reuse of reclaimed wood. The steps here included go from the use of laser scanning technologies for the creation of a digital library of wood debris component, to the implementation of automated AI e robotic methods for wood pieces performance analysis and assembly, depending

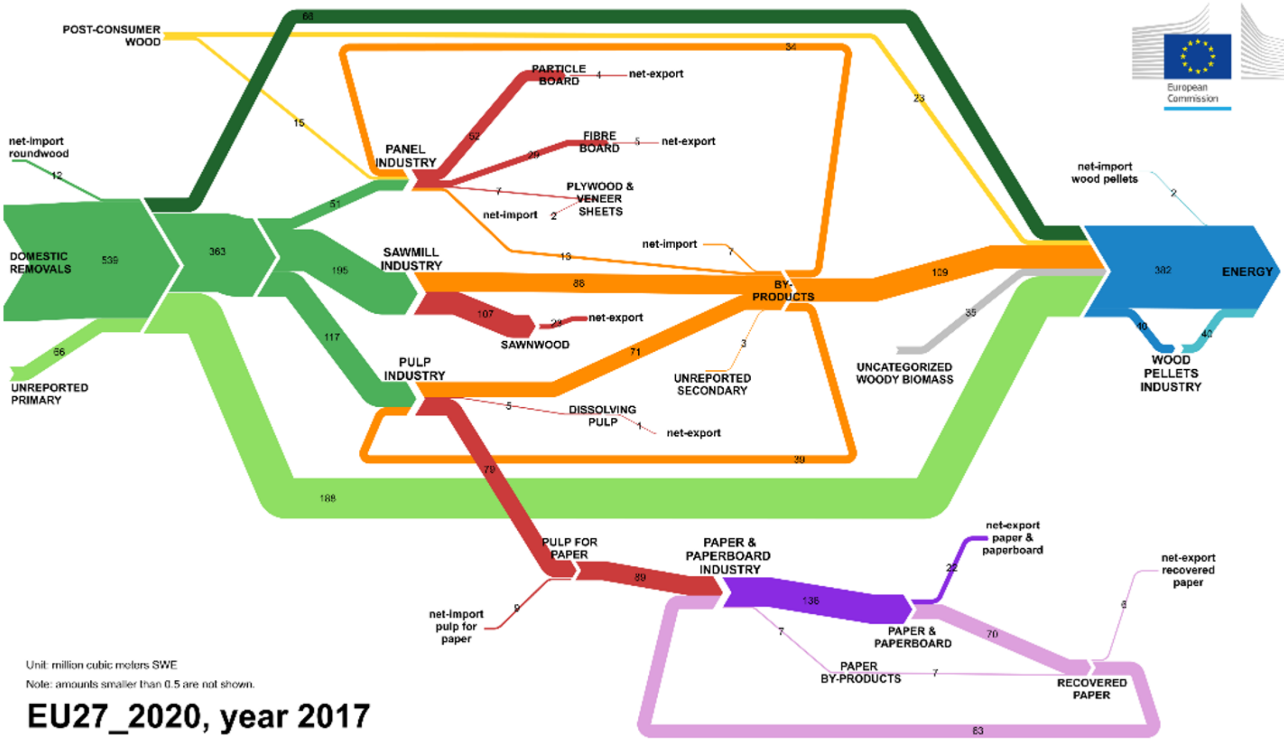

FIGURE 2: Interactive Sankey diagrams of woody biomass flows in the EU and Member States (source: https://knowledge4policy.ec.europa.eu/visualisation/interactive-sankey-diagrams-woody-biomass-flows-eu-member-states_en).

on the specific quality and quantity of each single component.

In the second sub-section, the paper examines the upcycling of wood waste through digital and robotic fabrication. These applications are aimed at defining new materials from recycled wood that can demonstrate additional or completely different performance than wood itself.

4.2 A conceptual workflow for the reuse of reclaimed wood

4.2.1 Laser scanning and creation of a digital debris library

Working with wood waste often involves dealing with a highly diverse range of materials. In such cases, having a structured dataset that catalogues all the components, organized by size, quality, and conservation, can be instrumental in guiding designers to optimize conceptualization and anticipate issues that may arise during the assembly phase.

The work conducted by Yu and Fingrut at the UCL Bartlett School (Yu & Fingrut, 2022) offers valuable insights into the role of digital scanning technologies for controlling and classifying waste materials. In their research, the authors explored the development of a wood library, encompassing both regular and irregular forms, through the 3D scanning of waste, underused, and off-cut wood. This database was enriched with the acquisition of a digital 3D model, capturing relevant parameters and physical characteristics such as material texture. Additionally, a materials database was established, cross-referencing information with the corresponding models (Figures 3, 4).

4.2.2 Materials inspection and selection via AI and Machine Learning

Research has substantiated that 3D scanning can complete material recovery and establish a material library. However, 3D scanning has no means to detect defects within the material, and some materials still require having their mechanical properties tested in addition to the basic inspection.

In this context, the application developed by The Living with the Princeton Embodied Computation Lab delved into leveraging Artificial Intelligence for instructing computers in identifying knots in wood waste components, sourced from disused provisional structures and scaffolding (Benjamin, 2018; Gerfen, 2018). The researchers established a user-friendly website where individuals could discern and annotate whether a given image of wood exhibited knots.

Upon inputting this human-labeled data into a computer system, the Machine Learning algorithm demonstrated its capability, even in the preliminary phase, to discern the

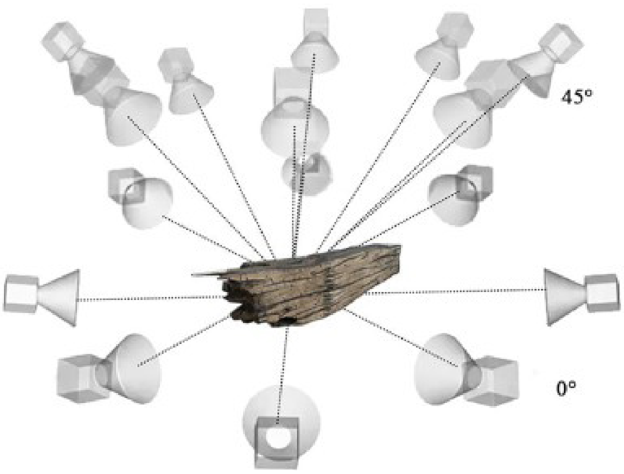

FIGURE 4a: Wood debris scanning (source: https://www.sciencedirect.com/science/article/pii/S0921344922004025).

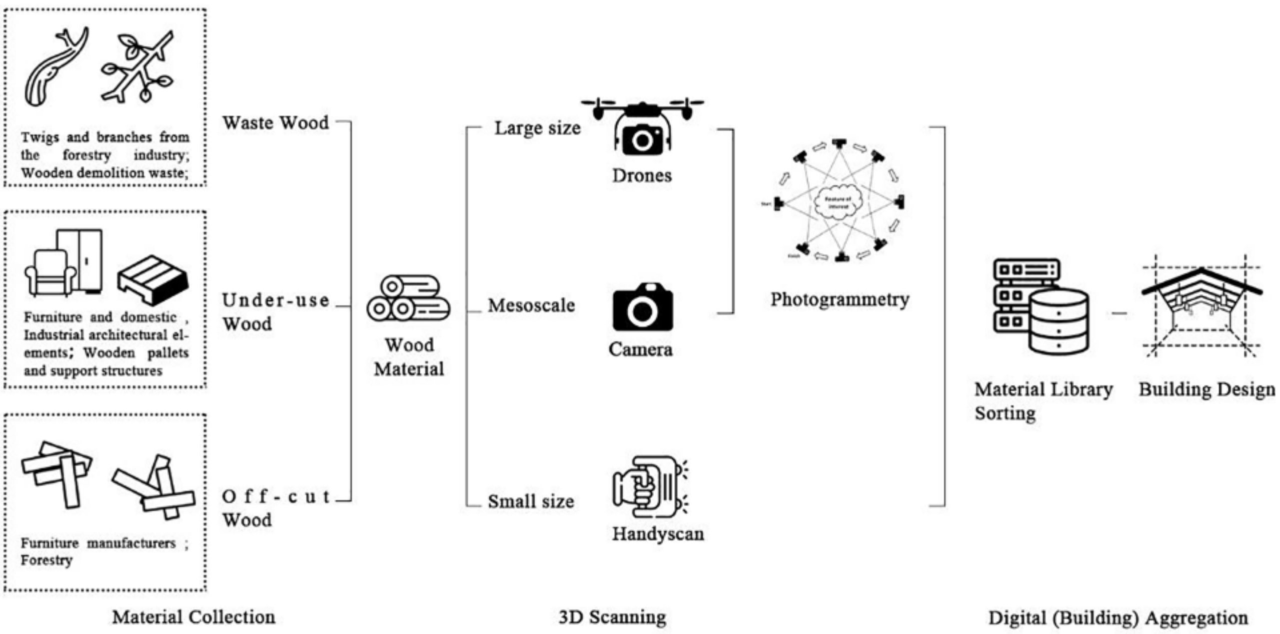

FIGURE 3: Method and workflow adopted by Yu and Fingrut (source: https://www.sciencedirect.com/science/article/pii/S0921344922004025).

FIGURE 4b: Regular and irregular material salvaged components digital library (source: https://www.sciencedirect.com/science/article/pii/S0921344922004025).

presence and location of knots. Subsequently, the identified knot locations from the computer were translated into files intended for a CNC machine tailored specifically for the fabrication of such components (Figure 5).

4.2.3 Robotic crafting and assembly

Robotic fabrication is a long-studied research track at at the IAAC – Institute for Advanced Architecture of Catalonia and is essential to build and craft structures digitally designed, where tolerances are lowered to the minimum and human error can put into risk the project.

In the Sourced Wood (IAAC, 2018) project, all the steps previously described (3D scan, digital library, material inspection and selection) are finalized with the fabrication and assembly with the use of robotic arms. The project is aimed to utilize waste wood in constructions and reshape them as falsework structures (Figures 6,7).

4.3 Expanding wood waste upcycling possibilities through Additive Manufacturing

4.3.1 Redesigning wasted objects with recycled wood fibers-infilled biomaterials

The “Planetary Boundaries Exhibition: Bio-Local Advanced Manufacturing,” is the result of the research carried by the Center for Information Technology in Architecture (CITA) at the Royal Danish Academy. The project aims to implement a small-scale manufacturing process utilizing locally sourced biomaterials in Denmark (Thomsen et al., 2022). An innovative robotic spraying technique uses a biopolymer derived from bone glue collagen (an animal industry waste itself) and wood waste fibers locally sourced. The application is both addressed to produce small architectural components and furniture, but its use could be broadened to the re-design and re-fabrication of damaged pieces (Figure 8).

4.3.2 Wood waste-filled biopolymers printing

CITA employs an analog material in the robotic printing process to produce large-scale 3D printed biopolymer elements with diverse material properties, allowing adaptation to distinct performance criteria associated with design, environmental factors, and boundary conditions (Nicholas et al., 2023). The design and fabrication of these elements necessitate a close integration of material specifications with local geometry descriptions and robotic control code. This interdependence precludes the application of conventional 3D printing methods such as slicing and boundary representation-based modeling. Instead, there is a demand for approaches facilitating the local and volumetric storage, querying, and manipulation of design, material, and contextual information through generative, parametric, and fabrication workflows.

To achieve this, a compositional pattern-producing network (CPPN) is employed to generate geometries. These

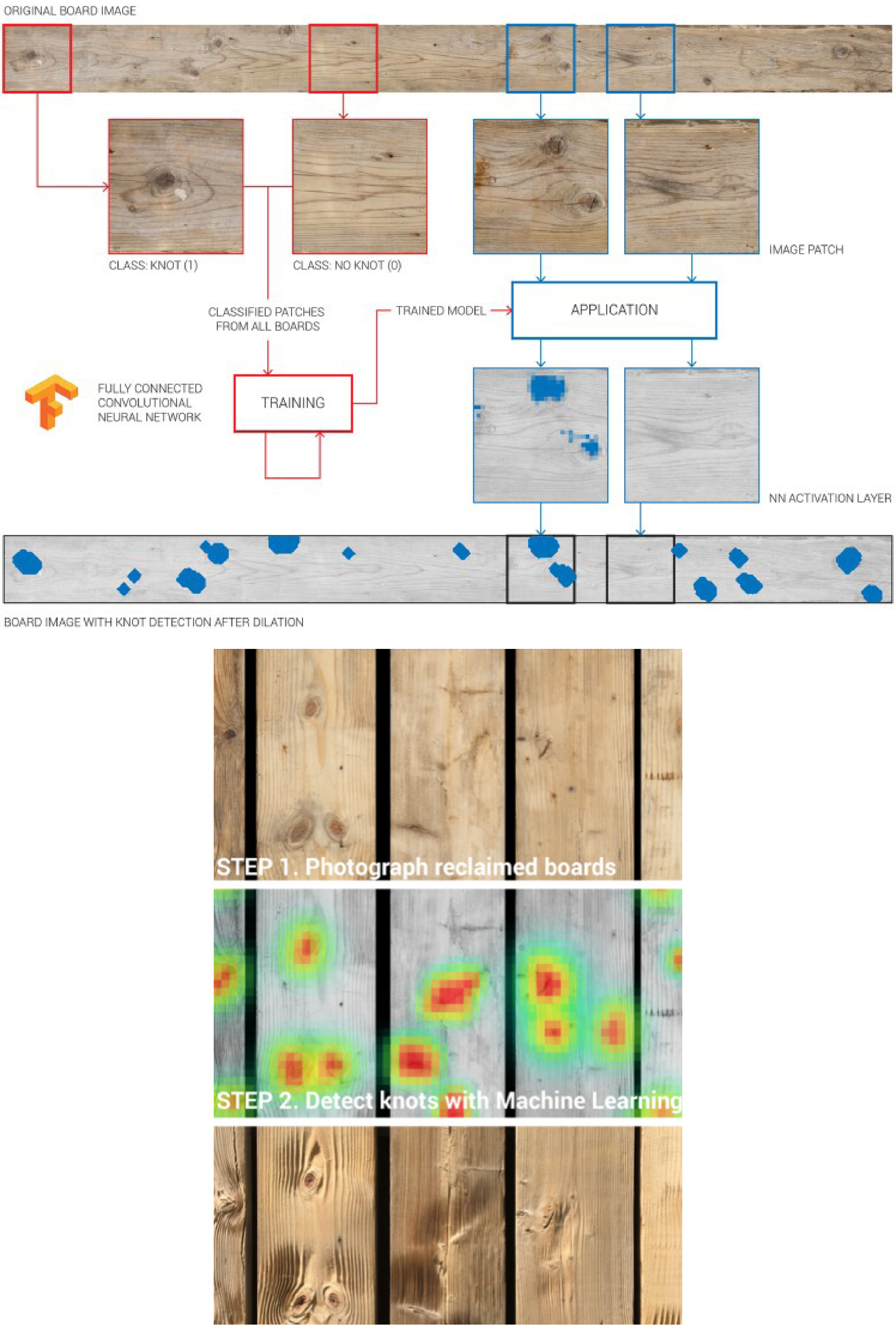

FIGURE 5: Machine Learning application for reclaimed wood knot automated detection (source: https://www.architectmagazine.com/project-gallery/embodied-computation-lab_o).

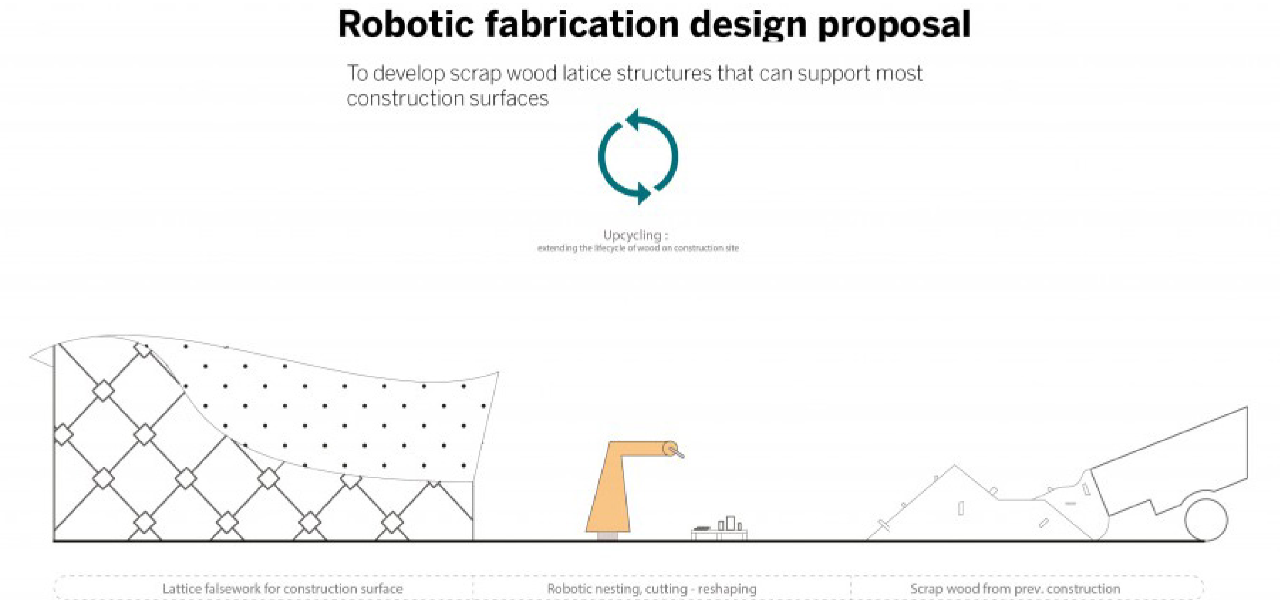

FIGURE 6: Sourced Wood robotic fabrication design proposal (source: https://www.iaacblog.com/programs/sourced-wood/).

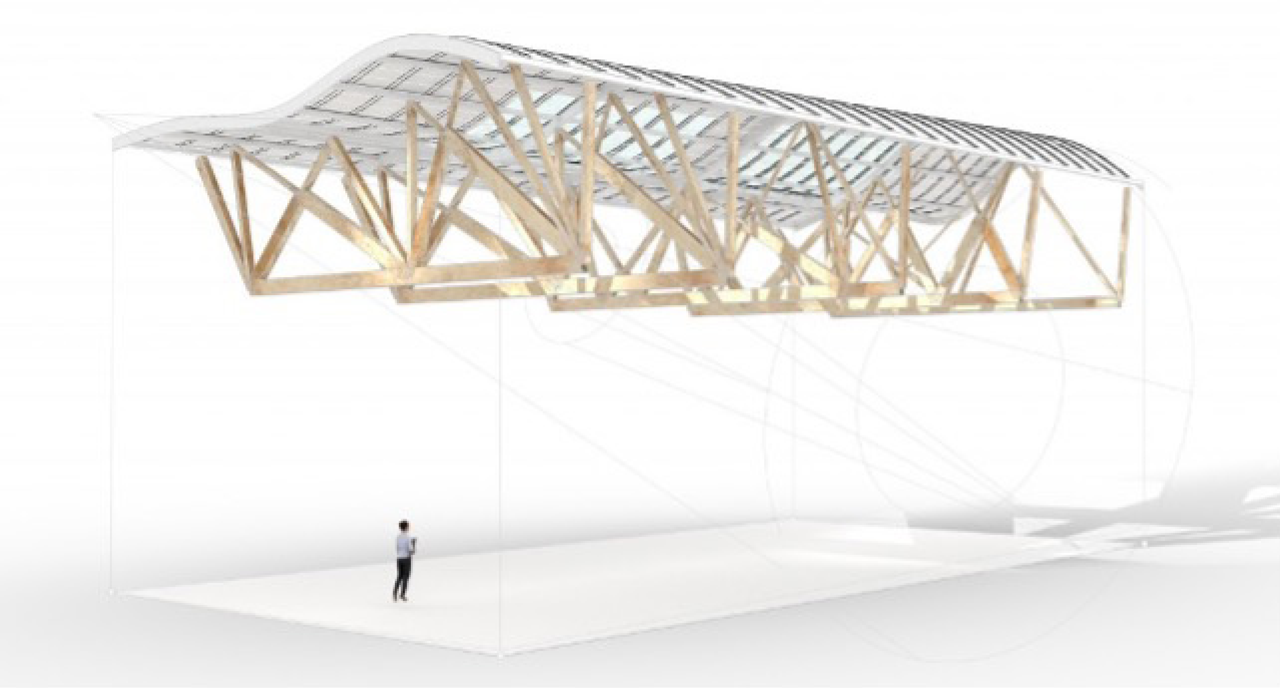

FIGURE 7: Sourced Wood robotic structural design vision (source: https://www.iaacblog.com/programs/sourced-wood/).

generated geometries undergo performance testing, and the outcomes inform subsequent iterations of the design process.

The efficacy of this workflow has been validated through the development of a customizable 3D-printed biopolymer-composite paneling system known as “Radicant”. This system, a built demonstrator measuring 7 × 5 m, was exhibited at the Aedes Gallery in Berlin during 2022/23. The “Radicant” collagen glue wall serves as a bespoke wall-paneling system, constructed from a biopolymer composite reinforced with various cellulose types sourced from waste products (Figure 9).

5. RESULTS DISCUSSION: ENABLING TECHNOLOGIES AND DESIGN CONSEQUENCES FOR AN IU APPROACH

The analyzed case studies allow to identify the enabling technologies for an IU approach to wood waste upcycling. Altough separately reporting reuse and recycling, these two workflows can be intended as inherently linked as the components that can’t be no longer reused (e.g. due to their loss of performance throughout the life cycles) can undergo recycling, thus minimizing the need for virgin resources.

Both in case of reuse or recycling, it emerges how the

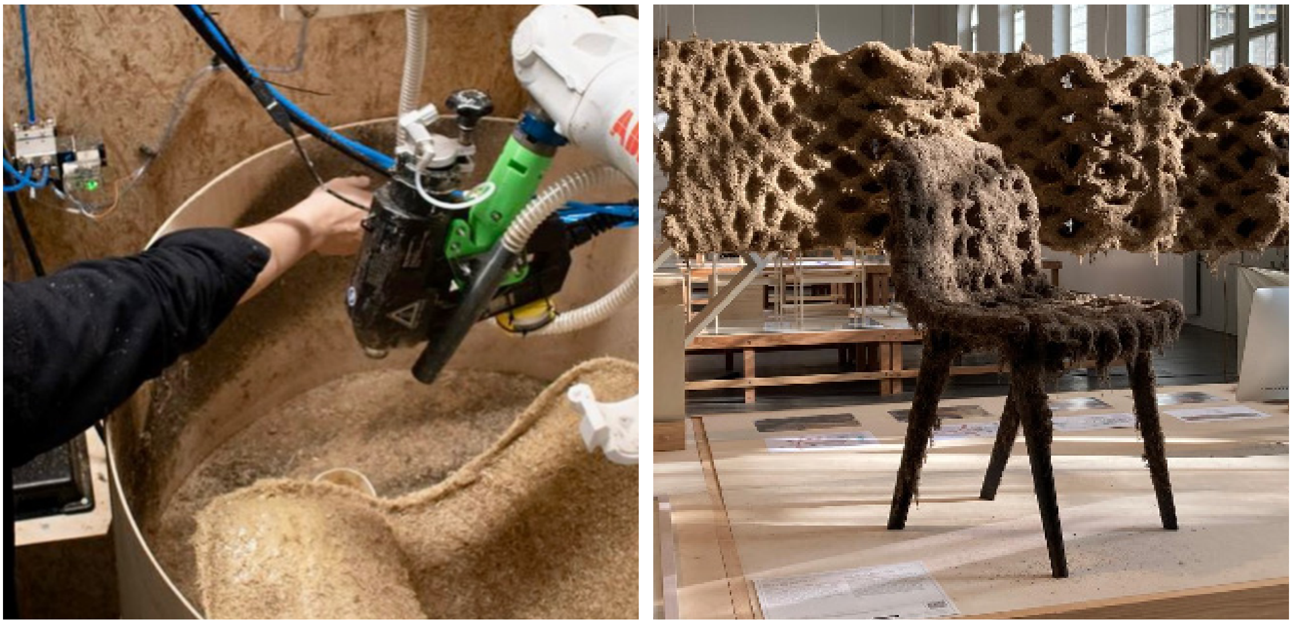

FIGURE 8: Process and prototyping of a "3D sprayed" chair, developed at Center for IT in Architecture, Royal Danish Academy, Copenhagen (DK).

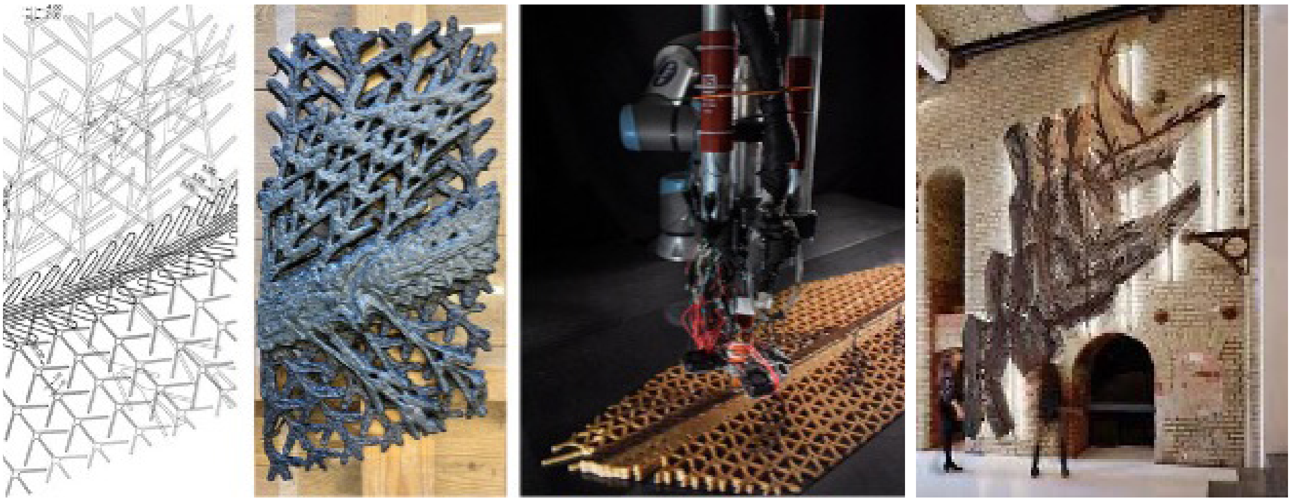

FIGURE 9: Printing and outcome of the "Radicant", developed at Center for IT in Architecture, Royal Danish Academy, Copenhagen (DK).

use of file-to-factory technologies is essential to transmit, amplify and keep the informational content of waste through upcycling within the recycled objects. 3D scanning technologies allow to record dimensional and physical features of the waste components; AI and ML integrated inspection tool are helpful in the automation of material verification and in the supporting the definition of the reuse of recycling strategies; advanced design and fabrication technologies open opportunities for novel material organization, that couldn't be otherwise pursued.

Nonetheless, it must be underlined how the presented applications are still far from becoming replicable best practices. The reseasons behind this gap between the laboratory scale and the industrial readiness can be traced in the lack of advanced expertise among the operators and the high time and cost rates of these experimentations. In the first case it is likely to imagine the gap filled by the next generation of praticitioners, that are currently gaining these new competences. In the second, it emerges how this kind of experimentation lies on a radically different conception of building and design production supply chain, entirely based on digital workflows and integrated information exchange protocols, throughtout all the buildings or components life cycle, between architects, engineers, clients, supplier, producers and maintenance operators. All these enabling technologies can work in one digital ecosystem, thus reducing the information loss due to data exchange and allowing for a greater quality control.

Compared to the existing options for wood waste recycling, such as panel boards production, the presented application demonstrate how an IU approach guarantees much more design freedom and production possibilities.

Indeed, it emerges how pursuing IU means to rediscuss traditional design paradigms towards a new design concept, in which material features, formal investigation and fabrication techniques are now sequential phases of the design process, but rather different dimensions of the same design moment.

The unpredictability of waste materials can leave place to a more controlled material definition, in which matter itself is programmed upon specific design intentions; or otherwise, design can be lead in a generative way by the material features and inner "tendency". At the same time, fabrication can be customized and adapted according to different material processes or can provide pivotal feedback regarding the design possibilities offered by the material. In the case of IAAC or The Living, the availability of components and its features is a critical driver for the whole design process, but at the same time the use of robotic fabrication allows to customize every single piece to be adapted to a specific design intent.

In the case of CITA's bioprinting, the balance between recycled wood and binder is defined by the printing possibility provided by the 3D printer, which is in turn the result of the customization of an universal collaborative robot. These linked parameters (material formulation and machine features) are both design driving, informing the design process according to the production capacity, and yet design driven, as they can be still modified according to specific design need.

From both cases, it emerges an unprecedented complexity that can be only successfully handled by using computational technologies, and that can lead to an unexperienced design freedom.

6. TESTING INFORMATIONAL UPCYCLING IN THE MADE IN ITALY INDUSTRY: THE FORWARD RESEARCH PROJECT

The theoretical framework and the conceptual workflows developed in this paper is currently under testing within the FoRWARD – Furniture Waste for Circular Design research projects. The research is aimed at implementing circular supply chains within the wood furniture SMEs, combining digitally-enabled technological advancement, knowledge transfer and clustering activities and educational initiatives.

Wood waste management represents a fundamental issue in the furniture industry in the wake of the transition to a CE model. The European Federation of Furniture Manufacturers (UEA) reports that 80% to 90% of the EU furniture waste in Municipal Solid Waste is incinerated or sent to landfill, with about 10% recycled (FURN360, 2017). Reuse activity in the sector is considered low and where it does occur, it is mostly through commercial second-hand shops, social enterprise companies or charities. European Environmental Bureau has identified the main challenges faced by the sector to move from a linear to a Circular Economy, mainly ascribed to materials and design, poor demand and consumer information, high costs of repair and refurbishment, reuse policy failure to be prioritized over recycling (EEB, 2017).

According to the DIGIT-FUR project (CFPIMM, 2019) forecasted vision for the furniture sector in 2025, digital tools will be crucial for the furniture industry and will be massively used, on the one hand for mass-customization for consumers (online tools, on demand manufacturing models, etc.) and on the other hand for digital manufacturing, from design (virtual modelling, artificial vision, etc.), to efficient manufacturing (Industry 4.0, robotics, additive manufacturing, etc.) and distribution (smart logistics, etc.).

Accordingly, the research methodology involves both digital technologies and wood waste-based biomaterials, implementing end of waste and metrics for circularity to assess the recycling potential of wooden scraps and wastes, designing new materials lifecycles and circular technologies for sustainable Made in Italy and design and depicting design methodologies for improving the wooden furniture sector according to the Circular Economy principles.

In particular, the experimentation will cover three main aspects:

1. the implementation of a Life Cycle Assessment methodology for bio-based waste-derived materials (wood scrap, natural fibers, cellulose, etc.) and digital design and fabrication processes (Artificial Intelligence and Machine Learning, Computational Design, Robotic Fabrication);
2. the assessment of the fabrication potentialities with digital technologies of the new materials, defining strategies for machines and/or materials customization;
3. the definition of possible design configurations, in compliance both with the machines specifications and the materials features.

The main goal of the FoRWARD project, nonetheless, is to fund an investigation to the new relationships designers and researcher are establishing with Technology in the Digital Age, and how this can be addressed to principles of necessity, i.e. CE and sustainability. In these terms, environmental sustainability only represents one aspect of the problem. The growing distance between advanced research and widespread design and craft practices, indeed, is urging for reflections about the social and economic impacts of digital technologies (Piscicelli, 2023).

For this goal, along with material and technical investigation, the FoRWARD research project intends to activate a correspondence between technological innovation and territories through the organization of collaborative actions, i.e. a Living Lab, that will take place in 2024 and will involve professionals, scholars, companies, artisans and students. In a CE perspective, upcycling relies on short-supply chain and local resources and waste. In this sense, an effective IU is actualized by computation, but is operationalized in an eco-socio-technical milieu. That is, the ecological intelligence of the upcycled material is the result of the original "redesign" of digital processes within the material culture of a Design Terroir. i.e.: «A delimited geographic space defined by a human community that builds throughout its history an ensemble of distinctive cultural traits, of knowledge and practices, based on an interaction system between the natural milieu and human factors. The know-how at play reveals an originality, confers a typicity and allows a recognition for products and services that originate from this space and for humans that inhabit it. Terroirs are living and innovative spaces that cannot only be assimilated to tradition. Design terroir represents an emergent eco-social movement in design and architecture. […] design terroir practitioners aim at increasing rich, direct environmental experience, and fair social development by promoting local and circular economy» (Pierce & Hermansen, 2023). In other terms, actualization provides for an answer; operationalization provides for a question.

Since February 2024, the activity is undergoing within a collaboration between the Department of Architecture, Federico II and the Center for Information Technololgy in Architecture (CITA), made possible also thanks to the ERASMUS PLUS KA1_ "University for Innovation" - Project Ref. n. 2021-1-IT02-KA131-HED- 000011202 mobility project promoted by the SEND Mobility Consortium, Italy.

In particular, the "recipe" for the bio-polymer 3D printing is developed within the CITA's Eco-metabolistic Architecture project (ERC H2020 grant N. 101019693) and will be implemented with the use of Italian forest (e.g. fir tree) wood flour and be tested in different possible application to furniture and interior component design (Krapez Tomec & Kariz, 2022).

7. CONCLUSIONS

In this paper, a conceptual framework is outlined to link CE to Computational Technologies and methods under the novel notion of "Informational Upcycling". Reclaimed resources, and wood waste in particular, is here defined and investigated as a computational material. These challenges that reclaimed wood poses to established design methodologies – uncertainty, non-linearity, unpredictability – require a brand-new theoretical approach that might be inherently related to Computational Thinking and Technological Design and can be particularly adapted to test the boundaries in the use of digital tools. This outline is informed by a case study analysis collected and reviewed for their innovation in terms of reuse and upcycling. Finally, the paper presents the FoRWARD – Furniture Waste for Circular Design research project, that aims to test the abovementioned approach to the Made in Italy furniture industry.

Therefore, the FoRWARD agenda for the operationalization of IU requires the definition of a set of questions, e.g.:

1. Who is the agent who will operate/benefit from our upcycle process, material or product? Where does this operation act?
2. What is the production scale we are addressing our upcycle process, material or product?
3. What are the desired/possible technical features we can get through computation?

Considering the definition of IU and the questions for its operationalization, a Living Lab (LL) approach appears to be a suitable solution to actualize Laboratory's computation within a Design Terroir. The LL approach allows for a hybrid environment in which different stakeholders can interact, tapping into the creative potential of each, within a systemic and structured framework of innovation (Eriksson et al., 2006).

This approach would interweave Laboratory's research methods and "affirmative" design (Oxman, 2016), adopting Living Labs to confront technological innovation with material culture and communities' requirements and collocating societal contribution as a vital step in research development, aiming at overcoming limitations of computation and traditional Open Innovation.

Within a Living Laboratory's research, IU can serve to redesign computation to be rooted in a material culture. The effects of this design operation would be the (re)activation of production patterns of a Design Terroir, leveraging digital methods to intercept and encourage emerging social and technical networks across the agents, lining up circular supply chains, formalizing tacit material knowledge, developing new competences and promoting inter-generational knowledge exchange.

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