

Designing with Nature. Interdisciplinary Approaches for Bioinspired and Sustainable Solutions in the Living Sectors

Marco Marseglia

Università degli Studi di Firenze

marco.marseglia@unifi.it

ORCID: 0000-0002-9406-5969

Tommaso Celli

Università degli Studi di Firenze

tommaso.celli@unifi.it

ORCID: 0000-0002-7944-0070

Edoardo Brunelli

Università degli Studi di Firenze

edoardo.brunelli@unifi.it

ORCID: 0009-0006-5412-9434

Francesco Cantini

Università degli Studi di Firenze

francesco.cantini@unifi.it

ORCID: 0000-0002-0017-1788

Gabriele Pontillo

Università degli Studi di Firenze

gabriele.pontillo@unifi.it

ORCID: 0000-0001-5839-7838

Giuseppe Lotti

Università degli Studi di Firenze

giuseppe.lotti@unifi.it

ORCID: 0000-0002-8066-5998

Abstract

The BIOPIC project represent an opportunity to develop and formalize a design-driven methodology for bioinspired design, integrating knowledge and tools from five disciplines: design, chemistry, biology, engineering, and agronomy. The project aimed both to create sustainable and circular bioinspired solutions and experiment with a collaborative model that could make interdisciplinary complexity operational. Grounded in a Research Through Design approach, the methodology positioned design as an epistemic coordinator between Hard and Soft sciences, enabling a reflective, iterative and inclusive process. Tools, such as Round Table and Google Form, activated a pragmatic interdisciplinarity, fostering shared design strategies and a common metalanguage. The paper addresses a specific research question: *Can we reconstruct the interdisciplinary, design-driven methodology for bioinspired design developed within BIOPIC?* The results, including proofs of concept for the Camper, Furniture and Nautical sector, three strategic and excellence domains of Made in Italy, demonstrate the feasibility of interdisciplinary bioinspired strategies oriented toward sustainability and circularity. Ultimately, the project reinforces an epistemological perspective of design as a transformative agent mediating between scientific, technological, and

Keywords

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INTRODUCTION

In the context of design and science, nature has always been a significant reference, both as a decorative and semantic inspiration—as seen in Art Nouveau—and as a functional and performance model, as evidenced by Leonardo da Vinci's studies (Fournier, 2018).

Over time, nature has evolved into a model, measure, and guide for the design of artificial objects, as exemplified in the concept of Bionics (Steele, 1961; Papanek, 1969), Biomimicry (Benyus, 2002), the approach defined as Biodesign (Myers & Antonelli, 2012), and finally in Bio-integrated Design (Cruz & Parker, 2022), where nature, from being an object of study and inspiration, becomes an active agency and part of the project as metabolism.

The relationship between nature and design has consolidated over time, defining a multitude of design approaches that could be gathered under the broad term Bioinspired Design (Gerola, 2023; Langella et al., 2022). Indeed, this term refers to a creative approach based on the observation of biological systems (ISO, 2015), with the objective of transferring natural models and operational logics of natural systems into technical systems. However, some authors (Blok & Gremmen, 2016; Ilieva et al., 2022; Gerola et al., 2023) affirm that when discussing nature-inspired design, certain ambiguities arise concerning sustainability. Gerola et al. (2023) highlight that philosophical considerations on nature-inspired design are mainly divided into two approaches: one that refers predominantly to innovation – Biomimetics and Bionics – and the other that focuses more on sustainability – Biomimicry (Benyus, 2002) –.

In particular, Blok and Gremmen (2016) define "strong biomimicry" as a design approach requiring a strict imitation of nature to achieve ecological and sustainability benefits, whereas "weak Biomimicry" refers to a freer form of inspiration that places greater importance on technical functionality. Ilieva et al. (2022) propose a conceptual framework that attempts to clarify what type of sustainability is pursued in bio-inspired design by categorizing approaches into Biomimicry for Innovation, Biomimicry for Net-Zero Optimisation, Biomimicry for Social Transformation, and Biomimicry for Biosynergy. The categories proposed by Ilieva et al. (2022) illustrate bio-inspired design solutions that range from techno-centric and market-oriented references – Biomimicry for Innovation – to solutions that holistically address all sustainability challenges – Biomimicry for Biosynergy –.

The terminological nuances and different levels of sustainability in bio-inspired design are clarified by ISO/TC 266 standards where, for example, the term Biomimicry refers to an approach strictly related to the concept of sustainability and, in particular, is defined as: "philosophy and interdisciplinary design approaches taking nature as a model to meet the challenges of sustainable development (social, environmental, and economic)" (ISO, 2015). The regulations highlight that the term Biomimetics is closely linked to the concept of innovation and, more specifically, refers to interdisciplinary collaborations between biology, technology, and other innovation sectors aimed at solving practical problems through the functional analysis of biological systems, their abstraction into reference models, and the applied transfer of these models into design solutions. All the proposed definitions, however, refer to multi- or interdisciplinary design approaches that are based on biology with the aim of solving complex design problems.

Disregarding the terminological nuances of the different nature-inspired design approaches proposed in the regulations, we can affirm that the project presented in this paper adopted a bio-inspired design approach that is highly interdisciplinary, with the objective of increasing the sustainability and circularity of the involved production sectors.

The discourse on bio-inspired design is in fact inextricably linked to the debate on the relationship between different fields of knowledge and disciplines, understood as multidisciplinary, interdisciplinarity, or transdisciplinarity (Max Neef, 2005).

Authors such as Marshall and Lozeva (2009) and Zwart (2019) outline the types of knowledge and disciplines involved in bio-inspired design, inviting us to understand the various biomimetic design approaches as part of an entire discourse domain that brings together scientific disciplines, technical practices, and heterogeneous social promises that take nature, natural organisms, and ecosystems as models for better design. Although the intentions, results, and approaches through which different disciplines collaborate in bio-inspired design projects are clear, the concrete methodology through which these disciplines effectively dialog, sharing ideas, methods, and tools within the design process, remains poorly mapped and formalized. How do scientific, technical, and design knowledges actually manage to interact in the context of bio-inspired design? What are the processes, common languages, decision-making dynamics that regulate their interaction? What are the methods and tools involved? These questions induce us to define a methodology for collaboration among the different knowledge domains on how to contribute to this emerging field of research. Specifically, in the *BIOPIEC project – BIOinsPired deslgn solutions for the living seCtor* – carried out under the PNRR (*National Recovery and Resilience Plan*) PE11 “Circular & Sustainable Made in Italy” programme, bio-inspired design strategies were investigated involving researchers specialized in design, chemistry, industrial engineering, mechanical engineering, agronomy, and biology from five Italian universities – *University of Florence, Polytechnic University of Bari, Polytechnic University of Milan, Polytechnic University of Turin, and University of Palermo* –. The BIOPIEC project explored bio-inspired design strategies to enhance circularity, sustainability, and resource efficiency in the Made in Italy industries. In particular, the research focused on the Furniture, Motorhome, and Nautical sectors, three typical sectors of Made in Italy. Drawing inspiration from nature—such as the hierarchical porosity in bone structures and the modularity in biological systems—the project introduced innovative materials, coatings, and manufacturing techniques. The developed bio-inspired design strategies are meant to optimize the product life cycle and the production systems involved based on the concept of future-proof design (Van den Berg & Bakker, 2015). These sectors strongly need innovative approaches to increase circularity (Thormann et al., 2023); to this aim, BIOPIEC focused on bio-inspired design strategies including the optimization of materials and maintenance, the development of innovative materials, the improvement of surfaces and external coatings, and the facilitation of correct disassembly for maintenance or end of life. In this perspective (design for reduction, for disassembly, for maintenance, and for remake), the project developed tools, solutions and materials for: generative and parametric design; additive manufacturing; bio-inspired and functional materials; surface treatments for high-performance; sustainable and reversible

glues. For the Motorhome Sector, the concept proposes an innovative design and manufacturing methodology where the vehicle is no longer entirely handcrafted using traditional carpentry techniques but is instead digitally modelled, structurally evaluated, and produced through additive manufacturing and manual assembly. The developed design-driven innovation strategy draws inspiration from hierarchical porosity materials found in nature (Wagermaier et al., 2025; Wei et al., 2023), such as bamboo (Buonamici et al., 2019) and trabecular bone (Gibson, 1985), which serve as reference for some vehicle components to reduce material usage. Addressing the design challenge of material reduction, a vehicle component was digitally modeled using parametric design, and its resistance was evaluated through the finite element analysis (FEM) method. Additional solutions for this sector included the application of new tannin-based insulating layers and the study of reversible adhesives to enable vehicle refitting, increasing component circularity. Furthermore, a Life Cycle Assessment (LCA) was initiated to compare the environmental impact of the proposed solution with current production methods.

In the Furniture Sector, the design-driven innovation strategy focused on transferring a naturally occurring structure, the honeycomb conjecture (Hales, 2001), to develop an adhesive geometry for a reversible kitchen cabinet finish. The weak adhesive, based on a reversible bio-inspired glue, enables finish reversibility and stability through the honeycomb conjecture. Finally, in the Nautical sector, bio-inspired shapes were studied for various finishes, including panels, handrails, and handles, with the goal of optimizing material usage. The design-driven innovation strategy in this case was based on selecting bio-inspired geometries (e.g. Voronoi structures) that optimize material distribution and designing components in metal-loaded polymers, allowing the application of a surface metal electroplating finish.

The proposed solutions have reached a TRL (Technology Readiness Level) between 3 and 4, considering, on one hand, the strong rootedness of the sectors involved in traditional production and technological logics, and on the other hand, the innovativeness of a bio-inspired design approach within this context. From this perspective, we believe that the most relevant aspects of the research concern the dialogue between different types of disciplines – soft and hard sciences – which have laid the groundwork for future research developments.

In this article, we present a structured methodology designed to address existing gaps and to map the relationships among disciplines involved. The aim of methodology is to support effective and conscious collaboration between the various disciplines involved in bio-inspired design projects, so that design choices are guided by a multitude of knowledge domains. In addition, the research present new bio-inspired and sustainable solutions for the involved sectors.

METHODOLOGY

The research development process and the implementation of the Proofs of Concept (POCs) followed a Design-Driven methodology, meaning it was coordinated by the Design research group and structured into three main phases.

The first phase focused on analyzing the sectors involved in the project and identifying the design questions; the second phase aimed at establishing a shared meta-language among the disciplines involved, to strengthen the interdisciplinary nature of the project, define preliminary concepts and possible biological references to adopt; the final phase synthesized the design insights, leading to prototyping and validating the proposed solutions. The development of the POCs led to the definition of a bioinspired and design-driven innovation strategy, which evolved during the project following the Research Through Design approach (Frayling, 1993; Zimmerman, 2010). In practice, traditional design methods and related thinking approaches (Cross, 1981, 1982) were combined with bioinspired design methodologies and the Scientific Method, defining the overall methodology only at the end of the process. Therefore, the methodology adopted does not strictly follow a traditional Biomimicry approach – *top-down* and *bottom-up* (Speck et al., 2017) – but rather a hybrid approach (Langella et al., 2022), which involved the entire research group collaborating simultaneously, sharing and creating methods and tools.

In particular, in the first phase, based on the theories proposed by Max Neef (2005) regarding types of collaboration between disciplines, a multidisciplinary approach was adopted. In the second and third phases, the research groups integrated by sharing ideas, methods, and tools, collaborating in an interdisciplinary way and laying the groundwork for future transdisciplinary research. According to Max Neef's theories, the type of interdisciplinary collaboration developed in this research project can be considered pragmatic – purposive or pragmatic interdiscipline – with Design positioned at a higher level as coordinator and guide for the other disciplines involved.

PHASE 1 PRELIMINARY ANALYSIS AND DESIGN QUESTION

In the first phase, a multidisciplinary preliminary analysis of the sectors involved was carried out to identify the main design issues, with the goal of increasing product sustainability and circularity. Preliminary analysis data were mainly gathered through case study selection, literature review, and data collected from previous projects conducted by members of the research group.

This initial phase involved the various disciplines collaborating through a self-organized “Round Table” (Bach, 2005) with the objective of co-creating new forms of interaction and mutual understanding among disciplines, thereby fostering transformative processes of individual knowledge. The “Round Table” was structured around the theme of sustainability and circularity for the sectors involved in the project. Each discipline contributed by engaging in dialogue from its own perspective while simultaneously being influenced by the others through an open and horizontal discussion that fostered divergent thinking. The data collected were recorded on a digital worksheet and subsequently synthesized and catalyzed into a final graphic representation. Based on the expertise of the research group members, the following elements were identified: design questions, hypothetical bioinspired design strategies, and possible design solutions. This phase began with a multidisciplinary approach but evolved, thanks to the synergies that emerged during the “Round Table”, into interdisciplinary knowledge exchange.

PHASE 2 INTERDISCIPLINARY RELATIONSHIP AND CONCEPT DESIGN

Given the broad application scope of the three sectors involved and the wide range of technologies available to researchers, the analyses conducted in the first phase revealed a broad spectrum of potential solutions.

In the second phase, starting from the preliminary insights defined during the “Round Table”, efforts were made to narrow multiple visions into a few focused solutions. This was made possible through the analysis of a “Google Form”, created to identify and define a shared meta-language among the disciplines. The form allowed each researcher – already influenced by other disciplines during the “Round Table” – to further focus their design and research directions. In this sense, this phase marked the concrete emergence of interdisciplinary relationships.

The form analysis was conducted for each productive sector and developed in three consecutive steps, aimed at channelling ideas toward concrete, shared design solutions within the heterogeneous research group. For each sector involved, researchers were asked to provide proposals for: material optimization, structure/form optimization, and maintenance proposals during use or end-of-life stages.

Each proposal required researchers to indicate – via open responses – possible solutions concerning: innovative materials, technological advancements, Product-Service System developments, and TRL impact. Based on the form results, the first step of analysis involved generating a “Word Cloud” graph to highlight the most frequently mentioned terms, helping to understand the most common and relevant topics among researchers. Next, the degree of interconnection and convergence between disciplines was examined. This involved mapping keywords to participating researchers to assess the weight and convergence of proposed solutions.

To this end, a “Network Graph” was created, where node size represented the weight of solutions, calculated as the number of keywords cited by a researcher multiplied by the expected TRL of the proposed solution. The edges represented the convergence of design ideas between researchers, calculated based on the number of shared keywords related to the same design topic. The final step of analysis consisted of reorganizing the keywords from the “Word Cloud” into categories and macro-categories, producing a “Sankey diagram” to converge ideas into shared potential solutions for the three focus sectors (Furniture, Motorhome, Nautic). These tools and visualizations were essential in defining the “Concept Design Boards” – “Summary Sheet” and “Concept Design Proposal” – for the following design phase. The “Summary Sheets” were developed by linking the results of the “Sankey diagram” with relevant biological strategies. The biological inspirations were identified consulting scientific literature and the open-source online database AskNature. They were then selected during an multidisciplinary brainstorming session, in which each researcher, drawing on their own background and expertise, contributed to the bio-inspired concept section with a descriptive explanation of how the selected strategies could be applied to the project. This process enabled the designers to synthesise the information from the bio-inspired concepts and develop their *Concept Design Proposals* through sketching.

PHASE 3 FINAL DESIGN, LAB SCALE PROTOTYPE AND VALIDATION

The final phase of the project involved the definition of final designs, the realization of some lab-scale samples, and the initiation of validation processes for the proposed solutions.

This phase marked a shift from previously established interdisciplinary collaboration to a more specific multidisciplinary interaction, in which individual disciplines collaborated directly only in part.

During the design phase, the Design research group, composed of designers and a biologist, carried out the design synthesis – from the biological reference to the technical product – through sketching, vector digital drawings for biological model abstraction, 3D modeling using generative and parametric design with *Grasshopper for Rhinoceros by McNeel*, photorealistic visualizations using *Keyshot by Luxion*, and specifically for the Motorhome Sector, rapid prototyping via sintering using *Sinterit Lisa Pro* loaded with PA-12 Smooth powder from the same manufacturer. For the Motorhome Sector, the design group, through three-dimensional models, interacted with the Agronomy group, which included Wood Technology experts and engineers responsible for conducting FEM (*Finite Element Method*) analysis.

The FEM analysis focused on current Motorhome structures compared to various bioinspired sections similar at Voronoi structures, including trabecular bone (Gibson, 1985) and the internal structure of bamboo, based on the study by Buonamici et al. (2019). For the FEM analysis, geometric manipulations and discretizations were performed using the open-source software *Salome-Meca*, while the finite element analyses were conducted using the solver code *aster*, both developed by EDF (*Électricité de France*). These digital samples were then subjected to imposed unitary forces to evaluate their deformation responses under bending, shear, and torsion. The samples were isostatically constrained (Gibbons & Chen, 2022) to allow free deformation in the desired directions (Wen et al., 2017). For this sector, a Life Cycle Assessment (LCA) was initiated by the Industrial Engineering research group to evaluate the current product and compare it with the innovative concept developed within BIOPIC. The comparative analysis is currently ongoing in the BIOPIC follow-up project, expected to conclude by the end of 2025.

Across all the POCs developed by BIOPIC, the Chemistry research group worked transversally on the design concepts, producing laboratory samples related to: sustainable inks for additive manufacturing, reversible glues for re-fitting or end-of-life finishes, and metallization of biobased polymeric materials. Injectability of inks for additive manufacturing was analyzed via extrusion experiments at constant speed, measuring the force required to extrude the material. Knowing the nozzle geometry, the apparent viscosity during extrusion was calculated using the *Hagen–Poiseuille* equation, and the morphology of the extruded filaments was investigated through *Scanning Electron Microscopy* (SEM). For metallization trials on biobased plastics, polylactic acid (PLA) was chosen a thermoplastic aliphatic polyester derived from renewable plant resources such as tapioca, corn starch, or sugarcane. PLA is one of the most widespread biodegradable and compostable plastics, especially used for additive manufacturing or packaging (European Polymer Journal, 2023). For metal deposition trials, copper was selected, and three types of deposition were tested: Chemical, Electrochemical, and Physical (PVD).

RESULTS

As previously introduced, we believe that the value of the research presented in this article lies in the methodology adopted throughout the entire process, which enabled dialogue between heterogeneous disciplines. As discussed in the introduction, nature-inspired design presents a structured and articulated framework of objectives and approaches, in which interdisciplinarity emerges as a key feature. However, the design methodologies – both theoretical and operational – and especially the ways of collaborating between different disciplinary domains involved in the project, remain less explicit and formalised.

For this reason, we consider it necessary to present the results of the BIOPIC project from multiple perspectives: on the one hand, from the point of view of knowledge and relationships between disciplines, namely how individual disciplinary domains contributed in the different phases of the research and how these contributions were integrated; on the other, from the perspective of tangible design outcomes. The following paragraphs describe the research results according to the three methodological phases previously illustrated.

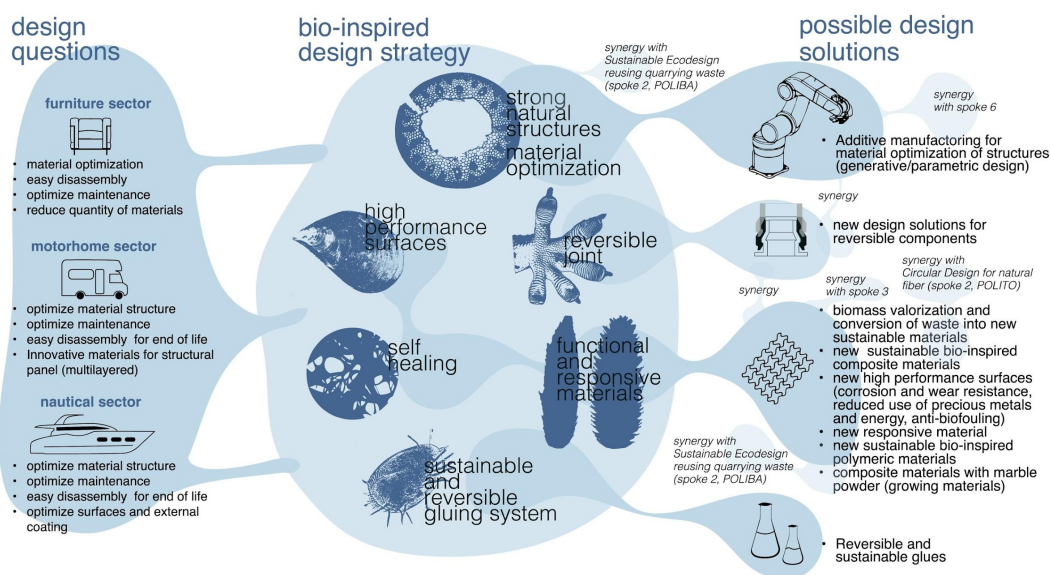


Fig. 1
Conceptual Sheet: on the left are the main design issues, in the center the possible biological strategies and on the right the possible solutions (Credits: The Authors, 2024).

MULTIDISCIPLINARY CONCEPTUAL SHEET

Thanks to the “Round Table” activity, four design questions were identified for each of the three sectors – Camper, Furniture, and Nautical – alongside a group of hypothetical bioinspired design strategies, transversal to all sectors, and a collection of potential design solutions. All these elements were synthesised into a “Conceptual Sheet”, which served as the first operational base to foster dialogue between the involved disciplines and to structure the “Google Form” used in the subsequent phase. The image shown in **Fig. 1** represents the first synthesis step between multi - and interdisciplinarity: this visualisation expresses hypotheses, knowledge, and early ideas generated by the research group, attempting a first graphic-visual integration of the knowledge related to the project theme. It is a descriptive and visual tool,

specifically designed to encourage interaction among the different disciplinary knowledge areas involved.

INTERDISCIPLINARY CONCEPT DESIGN

The results of the second phase derive from the compilation of the “Google Form” and led to the definition of initial design concepts, which were graphically synthesised by the Design research group. **Fig. 2** represents a graphical view of the form results through: “Word Cloud”, “Network graph” and “Sankey diagram” for each sector involved.

Sixteen research groups participated in the form: six in Design, five in Chemistry, three in Architecture, two in Engineering, one in Agricultural Sciences, and one researcher in Biology (affiliated with the Design group). The form generated a corpus of 6,077 words. To avoid bias in the “Word Cloud” frequency distribution, only words with greater intrinsic meaning (e.g., adjectives, nouns, verbs) were considered, while words with low semantic content, useful for sentence construction (articles, conjunctions, prepositions), were excluded. The “Word Cloud”, represented in **Fig. 2a, 2b and 2c**, revealed a frequency of 54 relevant words for the Furniture Sector, 32 for the Camper sector, and 14 for the Nautical sector.

For the Furniture Sector, seven out of eighteen researchers made a greater contribution to the project ideas (node size > 8), including three Designers, one Chemist, one Engineer, one Biologist, and one Agronomist. In the Camper sector, seven out of eighteen researchers made a greater contribution (node size > 8), including three Designers, one Chemist, one Engineer, one Biologist, and one Agronomist. In the Nautical sector, five out of eighteen researchers contributed more significantly (node size > 8), including one Designer, two Chemists, one Biologist, and one Agronomist. Regarding strong convergences (Edge value > 3) in the “Network” graph, shown in **Fig. 2d, 2e and 2f** – indicative of convergence in design ideas – it was observed that in the Furniture Sector, fourteen thick edges out of twenty occurred between researchers from different disciplines, and six out of twenty within the same discipline. Additionally, nine out of twenty thick edges were between researchers from the same university, and eleven out of twenty between researchers from different universities.

In the Camper sector, six thick edges out of seven were between researchers from different disciplines, one within the same discipline, while all seven were between researchers from the same university. In the Nautical sector, there was only one thick edge, which occurred between researchers from different disciplines within the same university. The analysis of thick edges thus reveals, especially in the Camper and Nautical sectors, the influence of university affiliation on the convergence of design ideas. The most frequently used words from the first phase were used to build the “Sankey” diagram of the third phase. First, they were grouped across all sectors into eight conceptual categories: Metals, Wood/Vegetal, Panels/Worktops, Coatings, 3D/Additive, Glues, Biofabrication, and Composites. Within these categories, synonymous or logically connected words were included (e.g., in the Furniture Sector, in the Metals category, “Electrodeposition” and “Recycled cast aluminium” were grouped). These eight categories, as illustrated in **Fig. 2g, 2h, and 2i**, were then organised into three macro-categories named: Target,

Materials, and Processes (e.g., in the Furniture Sector, within the macro-category Materials, the Metals category included the keywords Electrodeposition and Recycled cast aluminium).

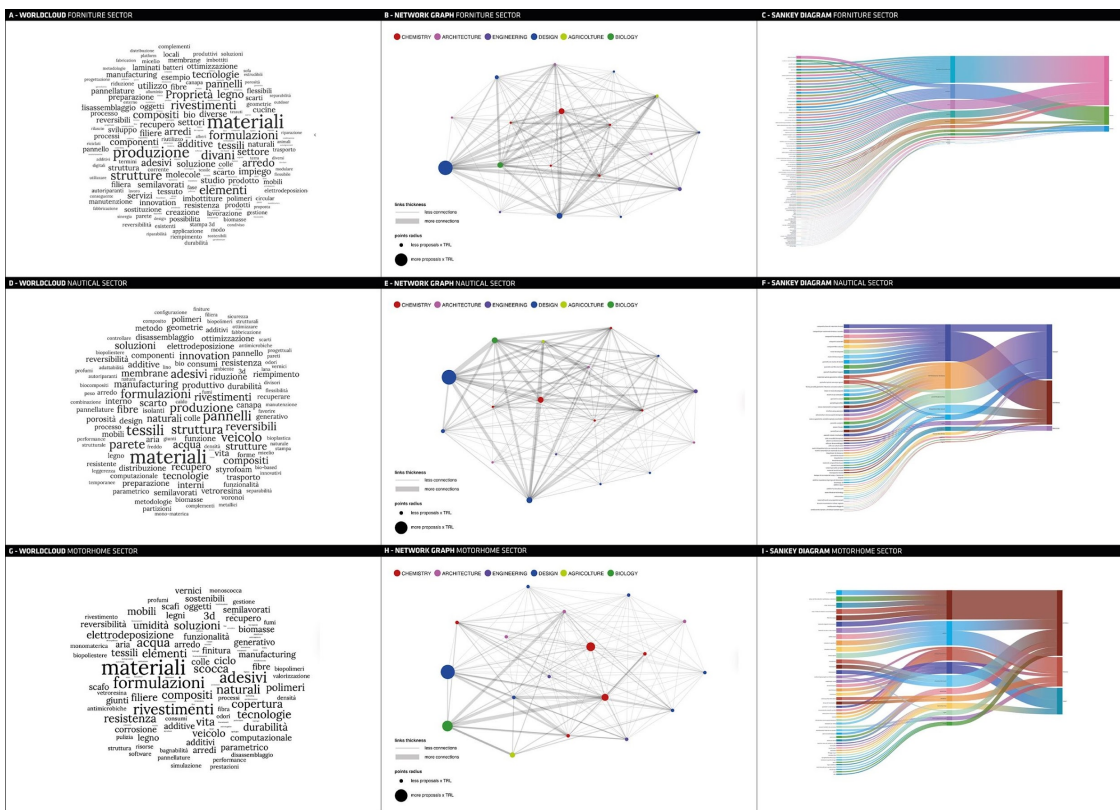

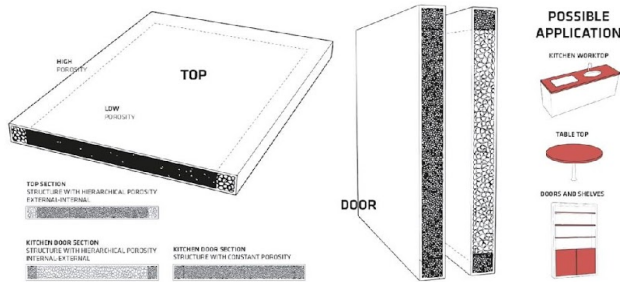

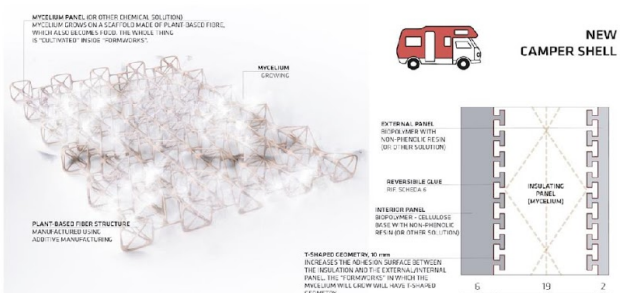
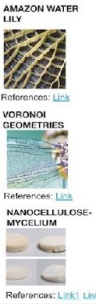
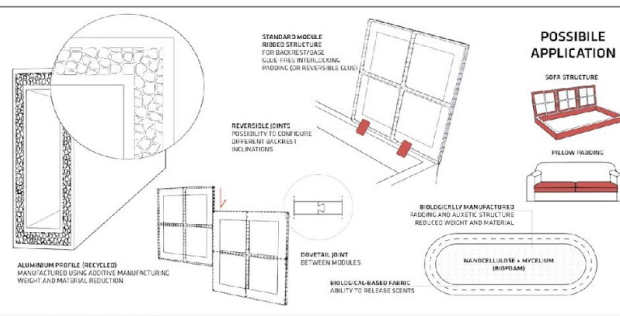

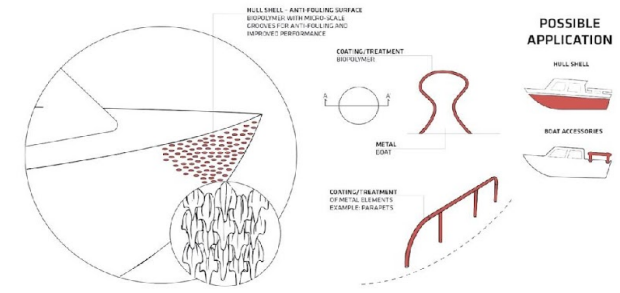

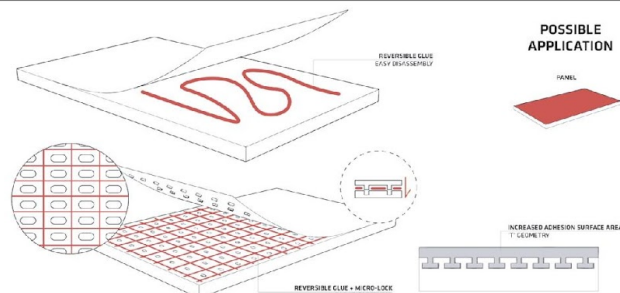


Fig. 2
The figure shows the results of the Google Form and the interdisciplinary connections: (a, b, c) Furniture Sector; (d, e, f) Nautical Sector; (g, h, i) Motorhome Sector (Credits: The Authors, 2024).

Based on the interpretation of the Sankey diagram, five “Summary Sheet” were created and organised according to the structure: Issue/Question – Materials, Target, Process – Biological Strategies, and Bioinspired Concepts, as shown in **Fig. 3a, 3b, 3c, 3d, 3e**. The selected Biological Strategies were mainly sourced from the asknature.org website or scientific literature, such as Hales (2001) for the Honeycomb Conjecture or Wei et al. (2023) for Hierarchical Materials. Based on the completed “Summary Sheet”, the Design research group further developed the ideas by visualising them in other boards called “Concept Design Proposals”, as shown in **Fig. 3f, 3g, 3h, 3i, 3l**.

The first concept, transversal for all the three sector, concerns a lightweight panel, characterised by a hierarchical porosity structure (Lakes, 1993) and specific surface properties, such as water repellency and antibacterial performance. The second concept refers to a new type of structure for perimeter panels of Motorhomes, incorporating bio-based insulation and reversible micro-joints to facilitate end-of-life management. The third concept is again based on natural structures with hierarchical porosity and involves lightweight modular aluminium structures for the upholstered Furniture Sector. The fourth concept, designed for the Nautical sector, proposes metallic surface coatings to increase durability and improve maintenance of key boat components. The fifth concept, which is relevant for all three sectors, involves an innovative reversible surface finish for panel coatings, using micro-joints and a reversible glue inspired by biological models, allowing easier maintenance and aesthetic upgradeability

Fig. 3 “Concept Design Boards” composed by “Summary Sheet” on the left and “Concept Design Proposal” on the right (Credits: The Authors, 2024).

| SUMMARY SHEET A | | CONCEPT DESIGN PROPOSAL A | | |
|---|--|---|---|---|
| <input checked="" type="checkbox"/> Furniture <input checked="" type="checkbox"/> Motorhome <input checked="" type="checkbox"/> Nautical Issue/Question .MATERIAL <input type="checkbox"/> fabric <input checked="" type="checkbox"/> wood/plant-based <input type="checkbox"/> metal <input checked="" type="checkbox"/> composite <input type="checkbox"/> additive <input checked="" type="checkbox"/> silice <input checked="" type="checkbox"/> accessories/coverings/surface finishes .TARGET <input type="checkbox"/> sofa <input checked="" type="checkbox"/> biopolymer/bio-based <input checked="" type="checkbox"/> coatings <input checked="" type="checkbox"/> panels/surfaces/foos <input checked="" type="checkbox"/> structure <input checked="" type="checkbox"/> resources during use <input type="checkbox"/> insulation (thermal/acoustic) .PROCESS <input checked="" type="checkbox"/> 3d/additive <input type="checkbox"/> biofabrication <input type="checkbox"/> coating <input checked="" type="checkbox"/> surface finishes <input checked="" type="checkbox"/> additive <input type="checkbox"/> biopolymer/bio-based | | Biological strategies  <p>SELF-CLEAN Citrus, Grape, Bay Leaf, Water, Olive, Bamboo, and Light References: Link 1, Link 2</p> <p>VORONOI GEOMETRIES/ CELLULAR STRUCTURES References: Link 1</p> <p>SELF-REPAIR References: Link 1, Link 2, Link 3</p> | Bio-Inspired Concepts <p>One-piece panel with water-repellent, antibacterial, water harvesting, controlled wettability, stain-resistant properties and with technical-mechanical characteristics similar to joinery panels but with a lower specific weight.</p> <p>The idea is to create two types of panel: horizontal (e.g. tops) and vertical (e.g. doors). The horizontal has a hierarchical porosity structure, the vertical has constant porosity or a reverse hierarchical porosity structure in order to allow the insertion of hinges. The panels should be easy to maintain/repair (self-healing, self-repair, self-cleaning).</p> <p>The hypothetical process of fabrication is additive manufacturing.</p> | Concept Design Proposal  <p>POSSIBLE APPLICATION KITCHEN WORKTOP TABLE TOP DOORS AND SHELVES</p> |
| <input type="checkbox"/> Furniture <input checked="" type="checkbox"/> Motorhome <input type="checkbox"/> Nautical Issue/Question .MATERIAL <input type="checkbox"/> fabric <input checked="" type="checkbox"/> wood/plant-based <input type="checkbox"/> metal <input checked="" type="checkbox"/> composite <input type="checkbox"/> additive <input checked="" type="checkbox"/> silice <input checked="" type="checkbox"/> accessories/coverings/surface finishes .TARGET <input type="checkbox"/> sofa <input checked="" type="checkbox"/> biopolymer/bio-based <input checked="" type="checkbox"/> coatings <input checked="" type="checkbox"/> panels/surfaces/foos <input checked="" type="checkbox"/> structure <input checked="" type="checkbox"/> resources during use <input type="checkbox"/> insulation (thermal/acoustic) .PROCESS <input checked="" type="checkbox"/> 3d/additive <input type="checkbox"/> biofabrication <input type="checkbox"/> coating <input checked="" type="checkbox"/> surface finishes <input type="checkbox"/> additive <input checked="" type="checkbox"/> biopolymer/bio-based | | Biological strategies  <p>VORONOI GEOMETRIES References: Link 1</p> <p>TURTLE SHELL References: Link 1, Link 2, Link 3</p> <p>WOOD-DECAYING FUNGI References: Link 1</p> | Bio-Inspired Concepts <p>New camper van shell, consisting of 3 parts: 2 mm outer biopolymer + 19 mm mycelium insulation + 6 mm inner biopolymer (tot. 27 mm, as at present)</p> <p>The insulation, made of mycelium, will grow on a scaffold made of wood-based (or other) fibre additive manufacturing (or other solutions from chemistry)</p> <p>The scaffold will be inserted inside formwork that will provide the ends of the panel with a T-shaped geometry in the last 10 mm. This geometry, which will also be present on the internal/external panel, will make it possible to increase the adhesion surface between the insulation and the panel, since a reversible glue (Ref. Concept 6) will be used to facilitate disassembly.</p> <p>As for the inner and outer panel, this will consist of a out- and impact-resistant, self-repairing biopolymer surface (or other solution)</p> | Concept Design Proposal B  <p>NEW CAMPER SHELL</p> |
| <input checked="" type="checkbox"/> Furniture <input type="checkbox"/> Motorhome <input type="checkbox"/> Nautical Issue/Question .MATERIAL <input checked="" type="checkbox"/> fabric <input type="checkbox"/> wood/plant-based <input type="checkbox"/> metal <input checked="" type="checkbox"/> composite <input type="checkbox"/> additive <input checked="" type="checkbox"/> silice <input checked="" type="checkbox"/> accessories/coverings/surface finishes .TARGET <input checked="" type="checkbox"/> sofa <input type="checkbox"/> biopolymer/bio-based <input checked="" type="checkbox"/> coatings <input checked="" type="checkbox"/> panels/surfaces/foos <input checked="" type="checkbox"/> structure <input checked="" type="checkbox"/> resources during use <input type="checkbox"/> insulation (thermal/acoustic) .PROCESS <input checked="" type="checkbox"/> 3d/additive <input type="checkbox"/> biofabrication <input type="checkbox"/> coating <input checked="" type="checkbox"/> surface finishes <input type="checkbox"/> additive <input checked="" type="checkbox"/> biopolymer/bio-based | | Biological strategies  <p>AMAZON WATER LILY References: Link 1</p> <p>HONEYCOMB STRUCTURE References: Link 1</p> <p>VORONOI GEOMETRIES References: Link 1, Link 2</p> <p>POMELO SKIN References: Link 1</p> <p>NANOCELLULOSE-MYCELIUM References: Link 1, Link 2</p> | Bio-Inspired Concepts <p>Lightweight additive manufacturing aluminium sofa frame. Standard and modular ribbed modules to make the sofa backrest and base.</p> <p>The ribbed modules can be connected to each other through coverlet joints and will be connected to the structure through tilt-adjustable joints.</p> <p>The upholstery, with an asexual structure, will be made of nanocellulose + mycelium (biofoam) and will be positioned interlocking without the use of glues.</p> | Concept Design Proposal C  <p>POSSIBLE APPLICATION SOFA STRUCTURE FELLOW FIBERING NANOCELLULOSE + MYCELIUM BIOFOAM</p> |
| <input type="checkbox"/> Furniture <input type="checkbox"/> Motorhome <input checked="" type="checkbox"/> Nautical Issue/Question .MATERIAL <input type="checkbox"/> fabric <input type="checkbox"/> wood/plant-based <input checked="" type="checkbox"/> metal <input checked="" type="checkbox"/> composite <input checked="" type="checkbox"/> additive <input checked="" type="checkbox"/> silice <input checked="" type="checkbox"/> accessories/coverings/surface finishes .TARGET <input type="checkbox"/> sofa <input type="checkbox"/> biopolymer/bio-based <input checked="" type="checkbox"/> coatings <input type="checkbox"/> panels/surfaces/foos <input checked="" type="checkbox"/> structure <input checked="" type="checkbox"/> resources during use <input type="checkbox"/> insulation (thermal/acoustic) .PROCESS <input type="checkbox"/> 3d/additive <input type="checkbox"/> biofabrication <input type="checkbox"/> coating <input checked="" type="checkbox"/> surface finishes <input checked="" type="checkbox"/> additive <input type="checkbox"/> biopolymer/bio-based | | Biological strategies  <p>MICROSCOPIC SCALES References: Link 1</p> <p>CICADA WINGS References: Link 1</p> <p>COMMON MUSSEL References: Link 1</p> | Bio-Inspired Concepts <p>Surface coatings of ships' hulls with improved anti-fouling and hydrodynamic properties (e.g. morphology designed to reduce organisms' adhesion/proliferation and hydrodynamic friction)</p> <p>Surface treatment of metals for improved anti-corrosion properties (e.g., metal coatings, polymer coatings, etc.)</p> | Concept Design Proposal D  <p>POSSIBLE APPLICATION HULL SHELL METAL COAT COATING/TREATMENT OF METAL ELEMENTS</p> |
| <input checked="" type="checkbox"/> Furniture <input checked="" type="checkbox"/> Motorhome <input checked="" type="checkbox"/> Nautical Issue/Question .MATERIAL <input type="checkbox"/> fabric <input type="checkbox"/> wood/plant-based <input type="checkbox"/> metal <input checked="" type="checkbox"/> composite <input type="checkbox"/> additive <input checked="" type="checkbox"/> silice <input checked="" type="checkbox"/> accessories/coverings/surface finishes .TARGET <input type="checkbox"/> sofa <input checked="" type="checkbox"/> biopolymer/bio-based <input checked="" type="checkbox"/> coatings <input checked="" type="checkbox"/> panels/surfaces/foos <input checked="" type="checkbox"/> structure <input checked="" type="checkbox"/> resources during use <input type="checkbox"/> insulation (thermal/acoustic) .PROCESS <input type="checkbox"/> 3d/additive <input type="checkbox"/> biofabrication <input type="checkbox"/> coating <input checked="" type="checkbox"/> surface finishes <input type="checkbox"/> additive <input type="checkbox"/> biopolymer/bio-based | | Biological strategies  <p>OYSTER CEMENT References: Link 1</p> <p>ONYCHOPHORA GLUE References: Link 1</p> <p>WINGS LOCK TOGETHER References: Link 1</p> | Bio-Inspired Concepts <p>Development of a reversible glue (sustainable pressure sensitive glues) to allow easy disassembly of panels.</p> <p>Design of a panel in which the probable lower adhesion of the glue is compensated for by an micro-structuring system between the various parts that will make up the panel.</p> | Concept Design Proposal E  <p>POSSIBLE APPLICATION PANEL</p> |

DESIGN SOLUTION

The results of the third phase concern the final Proofs of Concept (POC) developed for the three sectors involved in the project, represented in **Fig. 4**, reaching a Technology Readiness Level (TRL) of 3.

For the Camper sector, a project was developed that proposes an innovative design and manufacturing methodology compared to current artisanal construction techniques. The project involves a motor home that is digitally modelled through computational and parametric design, structurally assessed via FEM analysis, and manufactured using a hybrid process of additive production and manual assembly. The FEM analysis was conducted by comparing, with a view to material reduction, current structural solutions (solid PVC profiles with fibreglass external layers and styrofoam insulation) to two bioinspired geometries with hierarchical porosity: bone trabeculae and bamboo. The results show that the trabeculae-inspired section, while maintaining the same stiffness and strength as current structures, enables a 43.6% material saving. The bamboo section, on the other hand, results in a 21.52% reduction but does not maintain the mechanical properties, resulting in a performance loss. The material savings from this analysis are currently being assessed by the Industrial Engineering group through comparative LCA studies, within the BIOPIC follow-up project, expected to conclude by the end of 2025. The POC for the Camper sector is thus a large structure made via additive manufacturing, which includes: the main structure – with a bioinspired section based on bone trabeculae –, the external skin of the vehicle, and the fixing points for the internal furniture. The project envisions the application of insulating material using reversible glue and the subsequent manual installation of internal linings. A full-scale prototype of a portion of the described structure is currently under construction within the follow-up project. At present, a study sample has been produced for the section inspired by bone trabeculae through an additive manufacturing process using sintering, illustrated in **Fig.5**.

For the Furniture Sector, a kitchen door was designed with a reversible and customisable surface finish, enabled by micro-joints and a weak adhesive system distributed geometrically following the bioinspired principle of the Honeycomb Conjecture. This principle states that the most efficient way to divide a surface into equal parts with the minimum perimeter is through regular hexagonal tiling (as in honeycombs); in this sense, bioinspiration is applied to optimise glue usage. The POC demonstrates the feasibility of a kitchen door that can be easily updated aesthetically, addressing both obsolescence and surface degradation, thereby extending the product lifecycle and generating economic advantages for the end user. This solution also opens new business model opportunities for producers, allowing reversible coatings to be replaced or updated over time.

For the Nautical Sector, the POC explores bioinspired forms for vertical finishing panels and accessories, such as handrails and handles, on boats. The proposed solution involves the use of metal-loaded polymers to facilitate electroplating (Giurlani et al., 2024), with the aim of reducing material consumption. By enhancing polymer compatibility with electroplating processes, the POC achieves high-performance surfaces with reduced metal use.

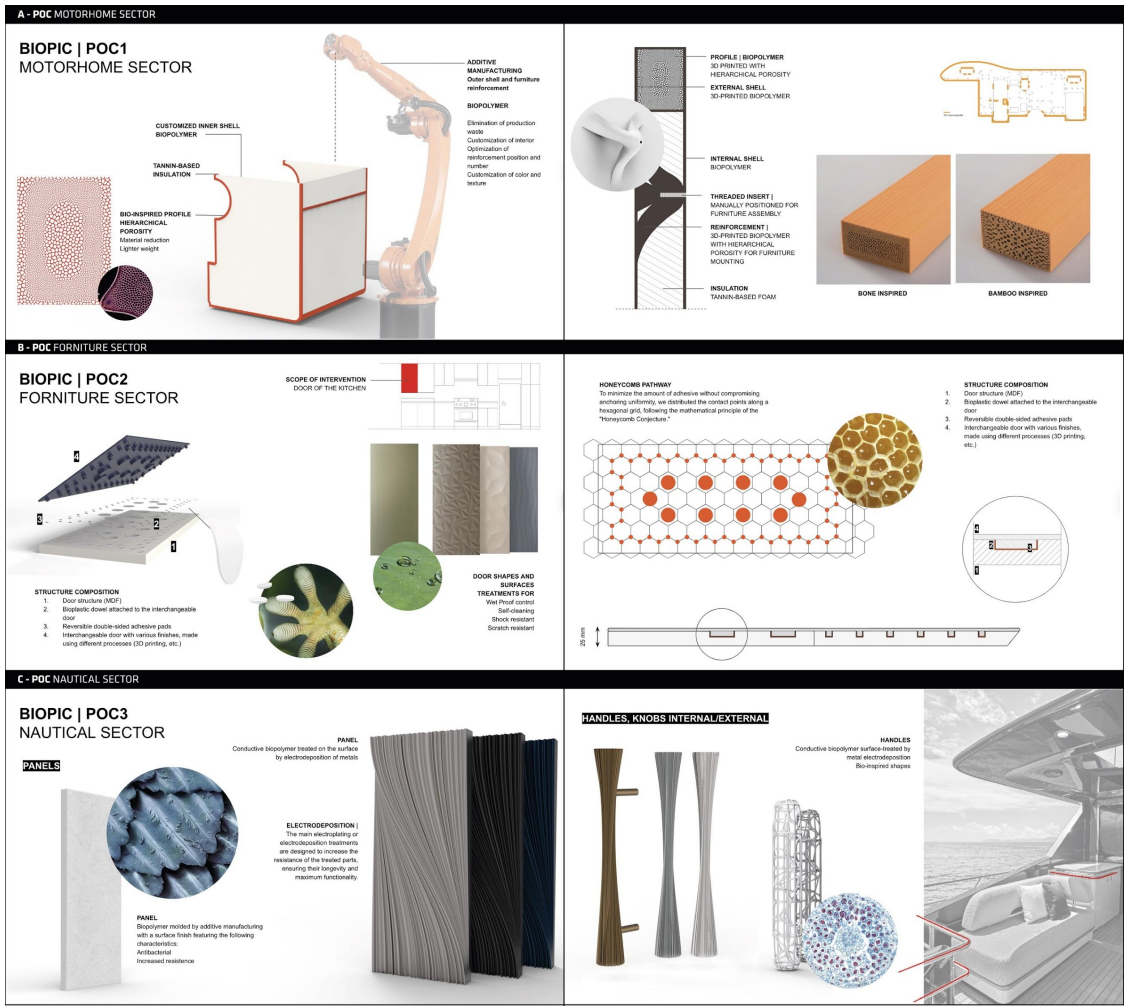


Fig. 4
The image shows the final projects for the three sectors involved: a) Motorhome Sector; b) Furniture; c) Nautical Sector (Credits: The Authors, 2024).

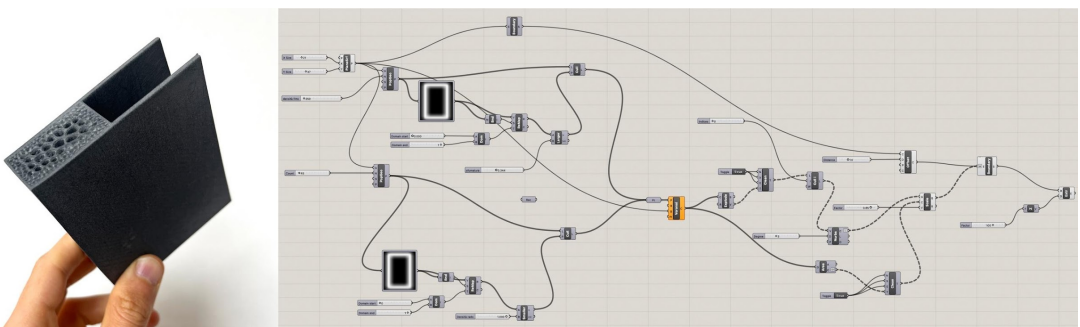


Fig. 5
A detail of the sample (on the left), Grasshopper interface of the algorithm used for 3D modeling (on the right) (Credits: The Authors, 2025).

DISCUSSION

BIOPIIC was a two-year project focused on identifying Bioinspired Design Driven Strategies within the framework of MICS – Made in Italy Circular and Sustainable – involving over 30 researchers from 5 Italian universities and 5 different disciplines. The project, which stands out for its heterogeneity both in terms of the level of familiarity among researchers and the number of participating disciplines, represents an excellent case study to analyse the methodology that developed and the role that Design played within it, both autonomously and in relation to the other disciplines. Moreover, the project aimed to develop products at a basic research level (final TRL-3); this allowed researchers to provide their contributions consistently throughout the entire duration of the project, avoiding, for example, the physiological discontinuity between scientific and technological disciplines that typically arises in projects of greater scalability.

Our work sought to formalise and document how collaboration among heterogeneous disciplines can be concretely implemented through shared tools, methodological phases, and a guiding role assigned to Design as a hinge between bodies of knowledge. **Fig. 6** shows the design steps described in the paper; it can be observed how the project phases alternated interdisciplinary, multidisciplinary and monodisciplinary moments, fostering a hybrid approach (Langella et al., 2022) between design practice, Bioinspired Design, and the Scientific Method. In particular, in the first phase, starting from mono- and multidisciplinary considerations, we moved towards tools that integrated knowledge in an interdisciplinary way in the central phase of the research; in the final part, there was a return to mono- and multidisciplinary modes of working.

What emerges in particular is that, with this type of collaboration between Hard and Soft Sciences, an attempt is made to reconcile two completely different approaches in terms of working method. Hard sciences operate through an inductive-deductive mode of thinking, whereas Design approaches the project through a divergent, intuitive and abductive mode of thinking (Cross, 1981; Lawson, 2004, 2006). Design and Hard Sciences thus adopt different cognitive styles which, in order to collaborate fruitfully, must find modes of cooperation aimed at defining a shared metalinguistic framework. The structure of the proposed methodology retraces the classic model of a Design project (Bonsiepe, 1993), characterised by an initial exploratory and divergent phase, a concept design and convergence phase, and a final phase of definition and validation of the design solution. The difference compared to a traditional Design project lies in the simultaneous presence of many heterogeneous disciplines, in addition to the theme of Bioinspired Design, which itself brings into play different methods and tools in the design practice.

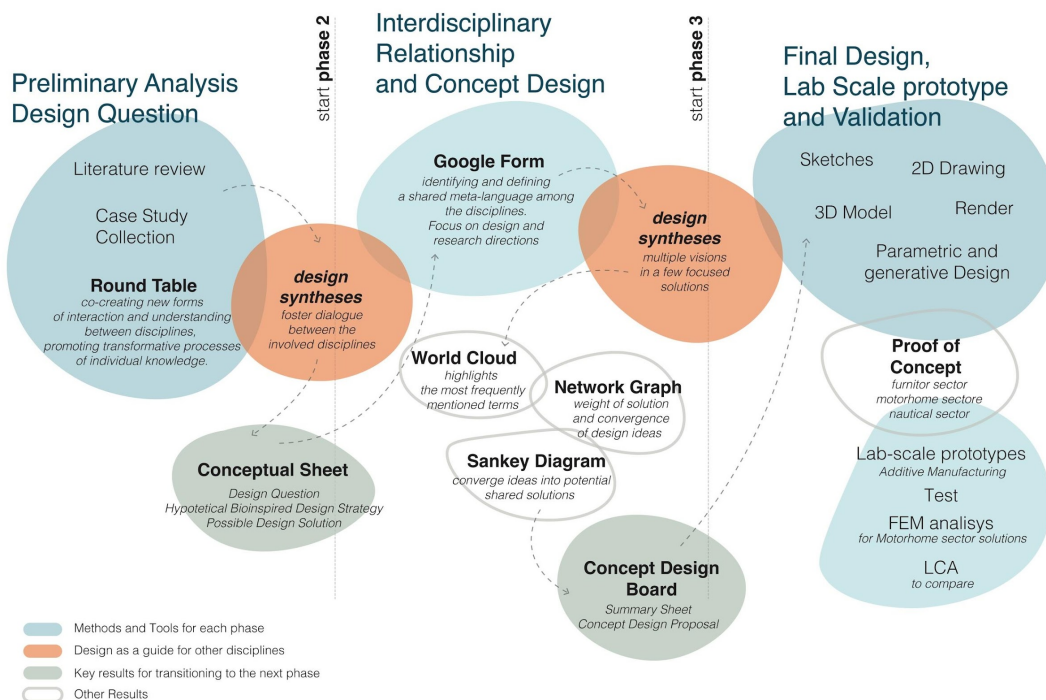
From the analysis of the tools used in this project – such as the initial “Round Table” and the “Google Form” – and from the methodological structure that developed during the research flow, we can affirm that Design played three key roles: interdisciplinary deductive mediator; clarifier, schematiser and visualiser of knowledge; and a cohesive factor bridging the different phases of the research process highlighted in the orange areas in **Fig. 6**.

After the initial exploratory phase, carried out through the “Round Table”, Design took on the role of an integrator of the collected data, generating a

“Multidisciplinary Conceptual Sheet” used as a visual tool to facilitate dialogue among disciplines and foster interdisciplinary relationships. Subsequently, through the “Google Form”, it assumed the role of deductive mediator of interdisciplinarity, taking on the responsibility of re-elaborating the complex and layered knowledge that emerged from the exploratory phase into concrete design hypotheses. In this synthesis process, it first elaborated a data visualisation through “Word Clouds”, “Networks”, and “Sankey” diagrams aimed at representing the knowledge that emerged in the dialogue among different disciplines; then, it developed concept design boards, synthesising and connecting specialist knowledge with design intuitions. Design thus built communicative tools that made explicit the references, problems and design potentials, fostering an operational convergence among the actors in the research project. The graphic representations generated were not only tools of analysis, but actual cognitive devices that allowed the semantic and operational convergences among the involved researchers to emerge. Finally, Design served as the discipline that provided methodological cohesion throughout the three phases of the research process, creating the connections between each step that were essential for its development. Despite the promising results achieved with the methodology applied in the Biopic project, it is important to note that it still needs to be tested on different projects within the field of Bio-Inspired Design in order to obtain a coherent and robust validation.

Fig. 6

The figure shows the methodology developed during the research. Specifically, the methods, tools, and key results are shown for the three main phases (Credits: The Authors, 2025).



CONCLUSION

The BIOPIC project represented a significant opportunity to experiment with and formalise a methodological approach to bioinspired design, integrating knowledge and tools from the 5 involved disciplines.

The main goal was not only the development of sustainable and circular bioinspired design solutions, but also the elaboration of a collaborative model capable of operationalising the complexity of interdisciplinary design. In BIOPIC, a broad methodological approach was tested, oriented not only towards the final product and solution, but above all towards the process itself that fostered collaboration among disciplines. The Design Driven methodology was developed through a Research Through Design process (Frayling, 1993; Zimmerman, 2010) and represents an attempt to make the interaction between different bodies of knowledge operational, while at the same time enhancing the role of design as an epistemic coordinator between Hard and Soft Sciences.

BIOPIC demonstrated how design, understood not only as a discipline but as an epistemological practice, can take on a guiding role in the coordination of heterogeneous disciplines, acting as a hinge between different ways of thinking: analytical on the one hand – Hard Sciences –, intuitive on the other – Soft Sciences – (Cross, 1981; Lawson 2004, 2006). The Design-Driven approach adopted enabled the activation of a process that was not linear, but iterative, inclusive and flexible, in which ideation and validation mutually reinforced each other. The three methodological phases – analysis of design ideas, conceptual convergence and design validation – enabled a conscious transition from multidisciplinary to interdisciplinarity, laying the groundwork for future transdisciplinary collaborations. This process enabled the configuration of a pragmatic interdisciplinarity (Max-Neef, 2005), where knowledge collaborates synergistically in the definition of design strategies. The tools adopted, such as the “Round Table” and “Google Form”, facilitated the construction of a shared metalanguage and the transformation of individual visions into collective design strategies.

The results achieved, both in terms of methodology and Proofs of Concept, demonstrate the feasibility and relevance of a bioinspired approach oriented towards sustainability and circularity in the Motorhome, Furniture and Nautical Sectors. Furthermore, the “Google Form” and conceptual boards were two tools with a shared purpose. The tools made it possible to channel multiple ideas into a few concrete solutions through a deductive approach, by cleaning and schematising the concepts both from a semantic point of view (Google Form) and from a graphic-visual point of view (concept boards). The strategies proposed not only respond to functional and environmental needs, but also promote a paradigm shift in how production and product life cycles are conceived within the sectors involved.

Referring specifically to the presented POCs, some technical challenges must be highlighted regarding industrialisation, such as scalability, costs and compatibility with existing production chains. These challenges were not fully addressed by the project and could represent a starting point for future research developments aimed at assessing actual technology transfer.

Despite the richness of the results, like any research project, BIOPIC presents some criticalities that could serve as a stimulus for future developments. For instance, there was not always a homogeneous level of integration among the disciplines involved; in particular, in the final phase, collaboration was reduced to a mono- and multidisciplinary approach. The formalisation of the proposed methodological model therefore remains partial and requires validation in other productive contexts and possibly also with different disciplinary

configurations – for example by introducing the human sciences – and design objectives.

BIOPIC proposes a potential methodology for bioinspired design, offering an operational model of interdisciplinary collaboration that can be replicated and adapted to other research and innovation contexts.

In conclusion, we believe that one of the main contributions of the BIOPIC project lies in the concrete activation of interdisciplinary practices in the field of bioinspired design. While most of the literature on the subject addresses multidisciplinary (Cangelosi, 2024) and interdisciplinarity (Donatelli et al., 2025; Raman et al., 2024; Ilieva et al., 2022), it does not actually demonstrate how different disciplines collaborate in practice, merely outlining a desirable framework of heterogeneous knowledge intended to tackle the complexity of bioinspired design.

BIOPIC therefore contributes to reinforcing an epistemological vision of Design as an active agent capable of integrating science, technology and culture, mediating between different ways of thinking and generating new knowledge through the construction of shared languages, methods and tools. From this perspective, Design is therefore not limited to translating existing knowledge into applied solutions, but acts as a reflective and transformative process in favour of sustainable innovation processes based on collaboration among heterogeneous disciplines.

References

- Bandi, A., & Kagitha, H. (2024). A case study on the generative AI project life cycle using large language models. *Proceedings of the 39th International Conference*, 98, 189–199
- Benyus, J.M. (2002). *Biomimicry: Innovation Inspired by Nature*. Harper Perennia: New York, NY, USA.
- Blok, V. & Gremmen, B. (2016). Ecological Innovation: Biomimicry as a New Way of Thinking and Acting Ecologically. *Journal of Agricultural and Environmental Ethics* 29, 203–217. DOI [10.1007/s10806-015-9596-1](https://doi.org/10.1007/s10806-015-9596-1)
- Bonsiepe, G. (1993). *Teoria e pratica del disegno industriale. Elementi per una manualistica critica*. Feltrinelli Editore, Milano, prima edizione fuori collana - First Edition in sc/10 1975. Pages 221-227, ISSN 0142-694X. [https://doi.org/10.1016/0142-694X\(82\)90040-0](https://doi.org/10.1016/0142-694X(82)90040-0)
- Cangelosi, G. F. (2024). A Multidisciplinary Approach for Bio-inspired Design: Interactions between drawing, AI, and parametric design. In SIGRadi 2024-*Biodigital Intelligent Systems-XXVI International Conference of The Ibero-American Society of Digital Graphics Proceedings*, pp. 815-826. CumInCAD.
- Cruz, M., & Parker, B. (2022). From Anthropocene to Biocene: Novel Bio-Integrated Design as a Means to Respond to the Current Biodiversity and Climate Crisis. In *Design Studio Vol. 4: Working at the Intersection*, 52-61. RIBA Publishing, ISBN: 9781003285410
- Cross, N., Naughton, J., Walker, D. (1981). Design method and scientific method. *Design Studies, Volume 2, Issue 4, 1981*, Pages 195-201. ISSN 0142-694X
- Donatelli, C.M., Vandenberg, M., Martinez, L., Schulz, A. K., Paig-Tran, E. W. M., Cohen, K. E. (2025). The Bioinspiration Feedback Loop: an interdisciplinary exchange of processes and progress between biologists and engineers. *Integrative and Comparative Biology*, 2025;, icaf128.
- Cross, N. (1982). Designerly ways of knowing. *Design Studies, Volume 3, Issue 4, 1982*,

<https://doi.org/10.1093/icb/icaf128>

European Polymer Journal Editorial Board. (2023). Editorial board. *European Polymer Journal*, 192, 112154. [https://doi.org/10.1016/S0014-3057\(23\)00337-3](https://doi.org/10.1016/S0014-3057(23)00337-3)

Fournier, M. (2018). Biomimesi - Quando la natura ispira la scienza (traslate by Erica Magnaghi), *Edizioni LSWR*. Originale title: Biomimétisme, quand la nature inspire la science. *Éditions Plume de carotte* (2016)

Frayling, C. (1993). Research art and design. *RCA Research Papers 1, n.1*. London: Royal College of Art, pp. 1 – 5.

Gibbons, M. M. & Chen D. A. (2022). Bio-Inspired Sutures: Using Finite Element Analysis to Parameterize the Mechanical Response of Dovetail Sutures in Simulated Bending of a Curved Structure. *MDPI Biomimetics*, 7, 82.

Gerola, A.; Robaey, Z.; Blok, V. (2023). What Does it Mean to Mimic Nature? A Typology for Biomimetic Design. *Philos. Technol.*, 2023, 36, 65. <https://doi.org/10.1007/s13347-023-00665-0>

Gibson, L. J. (1985). The mechanical behaviour of cancellous bone. *Journal of Biomechanics* 18, pp. 317-328. [https://doi.org/10.1016/0021-9290\(85\)90287-8](https://doi.org/10.1016/0021-9290(85)90287-8)

Giurlani, W., Pappaianni, G., Biffoli, F., Mariani, E.,

Bonechi, M., Giliberti, L., Tufarelli, M.; Franzo, P., Cianfanelli, E., Innocenti, M. (2024). What Is the Current State of Sustainability in the Decorative Electroplating Industry? A Close Look at New Practices and Advances. *MDPI Sustainability* 2024, 16, 5821. <https://doi.org/10.3390/su16135821>

Hales, T. (2001). The Honeycomb Conjecture. *Discrete Comput Geom* 25, 1–22. <https://doi.org/10.1007/s004540010071>

Ilieva L., Ursano I., Traista L., Hoffmann B., & Dahy, H. (2022). Biomimicry as a Sustainable Design Methodology—Introducing the “Biomimicry for Sustainability” Framework. *MDPI Biomimetics*, 7(2), 37. <https://doi.org/10.3390/biomimetics7020037>

ISO (2015). Biomimetics - Terminology, Concept and Methodology. *International Organization for Standardization*, 2015

Lakes, R. (1993). Materials with structural hierarchy. *Nature*, 361(6412), 511-515.

Langella, C., Vieira de Arruda, A. J., Di Bartolo, C. (2022). Revising Biomimetics: Opportunities and Ambiguities in the Bioinspired Design Approach. *Diid — Disegno Industriale Industrial Design*, 2022 (78), 10. <https://doi.org/10.30682/diid7822j>

Lawson, B. (2004), What Designers Know. *Architectural Press, Oxford*.

Lawson, B. (2006), *How Designers Think. The design process demystified*. Architectural Press, Oxford.

Marshall, A., & Lozeva, S. (2009). Questioning the theory and practice of biomimicry. *International Journal of Design & Nature and Ecodynamics*, 4(1), 1-10.

Max-Neef, M A. (2005). Foundations of transdisciplinarity. *Ecological Economics*, Vol. 53, Issue 1, 2005, 5-16. <https://doi.org/10.1016/j.ecolecon.2005.01.014>.

Myers, W., & Antonelli, P. (2012). Biodesign: nature, science, creativity. *Museum of Modern Art*.

Papanek, VJ (1969). The Tree of Life: Bionic. *The journal of Creative Behavior*, 3(1), 5-15.

Raman, R., Sreenivasan, A., Suresh, M., Nedungadi, P. (2024). Mapping biomimicry research to sustainable development goals. *Sci Rep* 14, 18613 (2024). <https://doi.org/10.1038/s41598-024-69230-9>

Speck, O., Speck, D., Horn, R., et al. (2017). Biomimetic bio-inspired biomorph sustainable? An attempt to classify and clarify biology-derived technical developments. *Bioinspiration & Biomimetics*, 12(011004). <https://doi.org/10.1088/1748-3190/12/1/011004>

- Steele, J. E. (1961). How do we get there?. *Bionics Symposium 1960, Living Prototypes. The Key To New Technology*, 487-490.
- Thormann, L., Neuling, U., Kaltschmitt, M., (2023). Opportunities and challenges of the European Green Deal for the chemical industry: An approach measuring circularity. *Cleaner and Circular Bioeconomy* 5, 100044. <https://doi.org/10.1016/J.CLCB.2023.100044>
- Van den Berg, M. R. & Bakker, C. A. (2015). A product design framework for a circular economy. *Product Lifetimes And The Environment, Nottingham Trent University*, 365-379.
- Wagermaier, W., Razghandi, K., Fratzl, P. (2025). A Bio-Inspired Perspective on Materials Sustainability. *Advanced Materials*. 2025 Jun;37(22). <https://doi.org/10.1002/adma.202413096>
- Wei, J., Pan, F., Ping, H., Yang, K., Wang, Y., Wang, Q., Fu, Z. (2023). Bioinspired Additive Manufacturing of Hierarchical Materials: From Biostructures to Functions. *RESEARCH*, 2023 Vol 6, Article ID: 0164. <https://doi.org/10.34133/research.0164>
- Wen, X., Yu H., Yan Y, Zong C., Ding H., Ma X., Wang T., Lei W. (2017). Influence of the shape of the micro-finite element model on the mechanical properties calculated from micro-finite element analysis. *Experimental and therapeutic medicine*, 14.2 1744-1748. <https://doi.org/10.3892/etm.2017.4709>
- Zimmerman, J., Stolterman, E., and Jodi Forlizzi (2010). An analysis and critique of Research through Design: towards a formalization of a research approach. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems (DIS '10). Association for Computing Machinery, New York, NY, USA*, 310-319. <https://doi.org/10.1145/1858171.1858228>
- Zwart, H. (2019). What is mimicked by biomimicry? Synthetic cells as exemplifications of the threefold biomimicry paradox. *Environmental Values*, 28(5), 527-549

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Marco Marseglia

Associate Professor, he has collaborated with the DIDA Department of the University of Florence since 2010 where he is currently coordinating member of the Design Laboratory for Sustainability. His research interests include Biodesign, its relationship with Life Sciences, and in particular bioinspired and biofabricated materials and products.

Francesco Cantini

Post-doctoral Fellow at the University of Florence, he collaborates with the Design for Sustainability Lab at DIDA and teaches Biodesign in the Eco-Social Design course. His research focuses on biodesign, biomimicry, and biofabrication, exploring the intersection between design, material technologies, and biology.

Tommaso Celli

Biologist specializing in genetics and microbiology. He is currently a PhD Student at the DIDA Department of the University of Florence. His research focuses on biodesign, particularly on the scientific and technological development of sustainable, biofabricated, and bioinspired materials.

Gabriele Pontillo

Designer and non-tenure-track assistant professor at the University of Florence, he explores the frontiers between technology and sustainability. His research aim to investigate the potential of parametric design applied to 3D printing to develop innovative artifacts with a strong focus on sustainability.

Edoardo Brunelli

PhD student at the DIDA Department of the University of Florence, he is a member of the Design for Sustainability Lab research group. His primary research interests lie in the collaboration between design and hard sciences, specifically in the fields of biodesign, bioreceptive design, and regenerative design.

Giuseppe Lotti

Full Professor and President of the School of Architecture at the University of Florence. He is President of the BA degree in Product, Interior, Communication and Eco-Social Design. He is the scientific coordinator of the Lab Design for Sustainability. From 2023 he is also the scientific coordinator of Spoke 2 of the PNRR PE11 MICS project.