CARDBOARD MICROARCHITECTURES FOR THE SUSTAINABILITY OF INTERNAL SPACE REDEVELOPMENT: A LIFE-CYCLE APPROACH THROUGH SCALED PROTOTYPE

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ABSTRACT

The use of cardboard microstructures is an innovative approach to improving the sustainability of interior space renovations. As urban areas face increasing pressure to use space efficiently, cardboard is becoming a versatile and eco-friendly material that can be adapted to meet diverse architectural needs. The objective of this study is to investigate the life cycle assessment potential of cardboard structures, with a particular emphasis on their capacity to mitigate environmental impact and foster adaptability in interior spaces. The utilization of cardboard, instead of traditional materials, facilitates lightweight and modular designs that can be easily reconfigured or disassembled, thus minimizing waste and resource consumption. Using principles of circular economy, these microarchitectures can be designed for reuse, recycling, or composting, thereby reducing landfill contributions and fostering a more sustainable urban environment. In this context, life cycle assessment plays a key role in identifying the environmental performance of cardboard microarchitectures. Through analysing energy consumption, material sourcing, manufacturing processes and end-of-life scenarios, we can identify opportunities for optimization. Moreover, cardboard microarchitectures present distinct prospects for enhancing indoor environments. Their adaptability enables the creation of multifunctional spaces that can adapt to user requirements, thereby promoting flexibility in urban living. Furthermore, incorporating biophilic design principles can enhance occupant well-being by incorporating natural elements within cardboard structures. In conclusion, the integration of cardboard microarchitectures into interior space redevelopment is a promising strategy for sustainability. By focusing on life cycle optimization, architects and designers can create environmentally responsible, adaptable and aesthetically pleasing spaces. This approach not only addresses pressing urban challenges but also contributes to a more sustainable future for architecture.

Keywords: digital manufacturing, microarchitecture, process optimisation, sustainable design, automation, educational experimentation.

1 INTRODUCTION

In an era of radical transformation, the building sector is called upon to respond to changing housing needs. In this context, technological research assumes a strategic role, proposing innovative and sustainable solutions for the definition of new architectural scenarios. In fact, the changing nature of needs, of the services offered and of the ways in which they are used leads us to reflect on the qualities of the built environment, emphasising the impact of the results of transformations on the natural environment and on the well-being of users.

The 2030 Agenda reminds us of the urgency of protecting the planet by implementing sustainable consumption and production models, promoting responsible management of natural resources and concrete actions against climate change [1]. In this context, innovation in technological and environmental design emerges as a key tool to promote changes in the desired direction. Following the 2030 Agenda, which emphasises the commitment to protect the planet through sustainable consumption and production, the sustainable management of its natural resources, and the adoption of urgent measures against climate change, so that it

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can sustain the needs of present and future generations, it is clear that the role of technological and environmental design of architecture is a pivotal tool with which it is possible to change the way in which transformation towards a decrease in impacts and consumption of energy and matter occurs [2]. In a century marked by the scarcity of raw materials, the climate emergency, the growing global demand for resources, and where design and production optimisation is asserted as a critical element, a possible strategy of action is the realisation of low environmental impact interventions using light and sustainable materials and the creation of spaces adaptable to different functions. Extremely relevant are not only product technologies, but also new process technologies that, applied to design and realisation, play a crucial role in generating an innovative integrated approach from conception to production, capable of minimising waste and maximising the life cycle of products.

2 BEYOND THE FORM: STATIC VS. DYNAMIC

The rapid evolution of housing needs, combined with the obsolescence of much of the existing building stock and the scarcity of resources for its redevelopment, calls for a paradigm shift in the approach to environmental and technological design. It is no longer a question of introducing static and permanent changes, which risk becoming obsolete before they even degrade, but of developing innovative design solutions. Experiences of experimentation in real contexts conducted by the research group, and the state of the art, would seem to support the use of small architectures, or microarchitectures, for interior space modifications, which, inserted into everyday spaces, can dynamically adapt to the needs of users, offering multiple types of use in both public and private contexts [3]. In line with the principles of the 2030 Agenda, which promotes environmental, social and economic sustainability, these design solutions aim to reduce environmental impact using eco-friendly materials and resource-efficient production processes [4]. At the same time, they favour the creation of flexible and adaptable spaces, capable of responding to the different needs of users over time. The suggested approach is, therefore, to overcome the traditional conception of architecture as a static and immutable entity, embracing a dynamic and sustainable approach, capable of combining technological innovation and environmental responsibility [5]. Cardboard microarchitectures can be easily modified and adapted to different needs, extending their life cycle and reducing the need for new construction. They represent a concrete example of the application of circular economy principles to architecture and design. This approach is based on the creation of closed-loop systems, in which materials are reused and recycled, minimising waste and environmental impact. Cardboard, in fact, is a widely available, recyclable and biodegradable material that can be easily reintegrated into the production cycle and is characterised by its lightness and ease of transport, low environmental impact and low cost [6], [7]. Cardboard microarchitectures can be effectively used in the creation of temporary set-ups for events, exhibitions and trade fairs; to create spaces for education and culture, such as libraries, classrooms and exhibition spaces; flexible and adaptable workspaces that meet the needs of companies and professionals. Indeed, cardboard microarchitectures represent a virtuous example of how the circular economy can be applied to architecture and design, offering innovative, sustainable and low-cost solutions for the creation of flexible and adaptable spaces. Moreover, these devices can dynamically transform the user's perception of the place and generate positive changes in the way that space is inhabited. The social dimension of sustainability highlights the need to develop projects that not only mitigate environmental damage but also improve the well-being of individuals and communities [8]. By thinking of architecture in this way, we provide the user with tools that, in addition to the creative aspect of the architectural object itself, allow them to analyse, know and experience the everyday environment in different ways and with different intensity.

Cardboard microarchitectures, thanks to their modular and flexible nature, allow interior spaces to be reconfigured quickly and easily, adapting them to different user needs. This dynamic approach to architecture encourages the creation of comfortable, stimulating and personalised environments, enhancing the well-being of individuals and communities. As part of the International Design and Building Workshop, held at L'Ecole Nationale d'Architecture de Marrakech (ENAM) from 8 to 18 December 2023 and as part of the didactics of the Technology of Architecture and Design degree workshop, in the Architecture degree course at the University of Chieti and Pescara 'Gabriele D'Annunzio' (Unich), a research and didactic experimentation on the described topic was initiated. The creation of a working group made up of students made it possible to conduct an interesting teaching and research experiment, the contents of which are summarised below.

3 OPTIMIZATION TECHNIQUES AND DIGITAL MODELLING

This study is set in the context of the recent evolution of design and production technologies, in which digital takes on a central and enabling role. In fact, digital technologies now characterise our daily lives and are the undisputed protagonists in the production sector, which is oriented towards a new industrial paradigm. In this scenario, Industry 5.0 is configured as a model in which the massive digitisation of production processes enables the automation of mechanised operations, optimising time and costs. The digital thread connecting design and manufacturing facilitates the customisation of construction elements, opening new frontiers to creativity and efficiency [9]. This provides multiple benefits within the supply chain, including product quality, process efficiency and resource optimisation. Regarding this last aspect, the introduction of digital in the field of building component production could optimise, both in terms of calculation and timing, all those operations that were previously entrusted to humans and not to machines. Indeed, computer graphics research is increasingly concerned with the analysis and high-level processing of geometric objects. By gaining a structural or functional understanding of 3D forms, researchers can tackle medium to high-level design problems for which machine calculations can replace or at least alleviate human production efforts [10]. This new type of process organisation would therefore lead not only to better results in the definition of structure and form, but also to a reduction in the percentage of errors and imperfections in the finished product, thus allowing for less dissipation of the resources used in the production process and the consequent lower production of waste material.

In this context, the development of innovative solutions relating to lightweight, recycled and recyclable materials, as well as the growing interest in prefabrication methodologies for the realisation of easily removable and reusable configurations, have assumed an increasingly important role [11]. Considering the theoretical–practical implications, the experimental work conducted, which had as its object the creation of a multifunctional honeycomb cardboard pavilion prototype, is described below subdivided into consecutive phases, logically ordered according to a well-defined didactic path, characterised by a circular scheme (Fig. 1) aimed at the continuous improvement of the process and the product. In this process, manual dexterity in the practice of drawing and modelling, which begins and concludes the entire process, is central, alongside which the use of computer-based instrumentation, which enriches and implements the empirical phases of the work, is equally important.

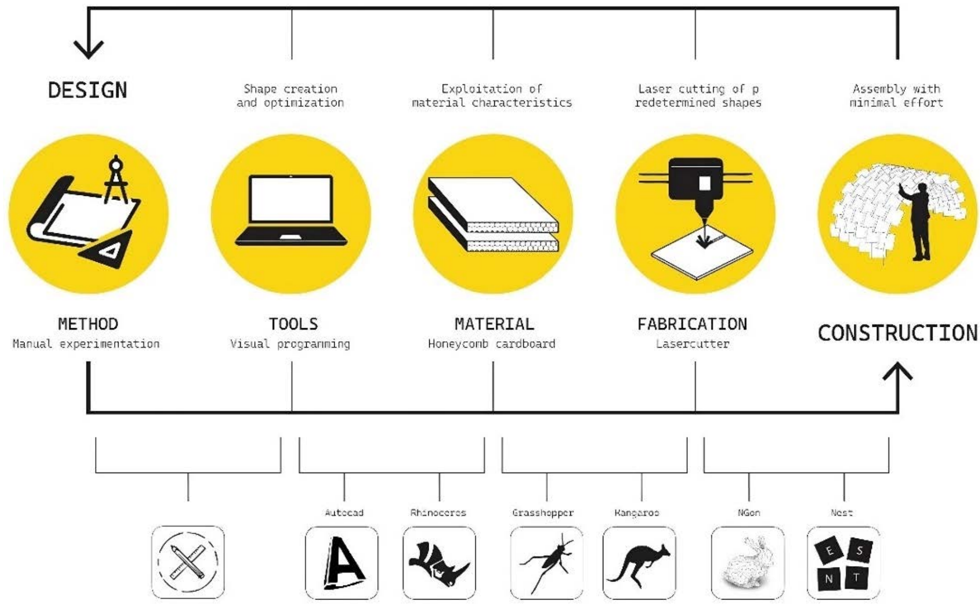

Figure 1: Conceptual map of the project cycle.

3.1 Step 1

The starting point consists of an initial experimentation based on manual drawing, in which the students can try their hand at the elaboration of different proposals for the basic elements that will go on to make up the final structure. The objective of this first phase of work consists in exploring new forms using classical drawing tools, thus promoting the physical and tangible search for innovative architectural solutions, for building elements characterised by different ways of aggregation, flexible and resilient (Fig. 2). During this first step, several proposals of building elements and assembly configurations were formulated, each of which was entirely designed and investigated by means of a hand-built model, to screen each proposed hypothesis and select the most convincing one. Referring specifically to one of these experiments, illustrated here as an example as it was developed for all phases, it is evident how the single piece was reworked several times (Fig. 3):

- The first series of elements, indicated as A-B-C, is characterised by main cuts tangent to the edges of the piece of 2.5 cm depth and two secondary cuts, inclined by 7° with respect to the (central vertical) reference axis, of 1 cm depth. During the assembly phases, however, an excessive rigidity of the parts created through the interlocking of the components just described was noted. Due to the too pronounced depth of the secondary cuts, it was not possible to obtain the correct flexibility of the elements, which, during assembly, were so cohesive that they did not allow the natural curvature of the structure.
- The second series of elements, indicated as A′-B′-C′, is characterised by main cuts tangent to the edges of the piece of 2.5 cm depth and two secondary cuts, inclined by 7° with respect to the (central vertical) reference axis, this time of 0.3 cm depth. Following the modifications made to the model, it was found, during the initial assembly phases,

that the structural elements had poor cohesion at the central cuts, which, being too small, did not stabilise the arch, leading the entire structure to collapse.

- The third and last series of elements, indicated with the initials A″-B″-C″, is characterised by main cuts tangent to the edges of the piece with a depth of 2.5 cm and two secondary cuts, inclined by 7° with respect to the (central vertical) reference axis, increased to 0.5 cm in depth. In view of what has just been described, it is clear how the last modification made to the central cuts proved to be a winner, allowing the structure to be stabilised and at the same time to develop the arc of the circle correctly.

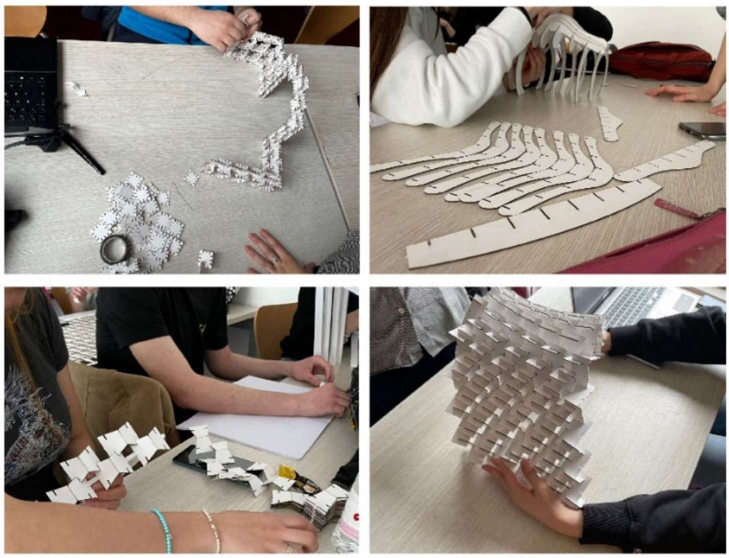

Figure 2: Manual experimentation with pavilions.

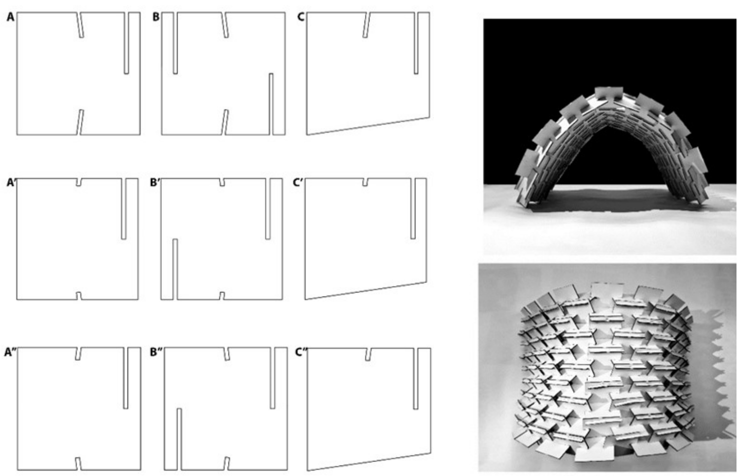

Figure 3: Pavilion first real model.

3.2 Step 2

Following these initial graphic elaborations and manual realisation of models, it was necessary to make use of digital tools capable of returning a very precise description of the object in question. The transition between manual and digital is a fundamentally important moment, in which the empirically conceived architectural element is analysed and tested by means of CAD programmes (AutoCAD) to which the starting information is transferred to obtain an updated and final version. In fact, modelling applied to design is a central tool within the design process as it allows for the exact conception of any architectural composition. The digital model, in fact, is a powerful means of fuelling the creative process and controlling the correctness of the design through the development of the idea in three dimensions. Considering that the design idea is essentially generated within the human mind in a three-dimensional way, it is clear how the use of real or virtual models, during the idea generation process, allows for greater control and a better ability to analyse the project itself, highlighting its criticalities and strengths. By virtue of the organic nature of the process, the design of forms cannot disregard the relationship with the material chosen for realisation: cardboard. A recyclable, ecological and lightweight material with a significant level of toughness and impact resistance, with good thermal and acoustic insulation properties. Considering the properties just described, cardboard is the material of choice for the construction of the final pavilion, which must be economical, ecological and light enough to be assembled and disassembled by anyone quickly and safely, without the need for additional tools.

To maximise the potential for reuse, designers must consider not only deconstruction but also future reconfiguration scenarios [12]. The importance of this last consideration is evident from the final definition of the pavilion's structural components, as, after refining the characteristics of the basic element through digital control tools, it was useful to test an initial assembly of the structure in virtual mode, using 3D modelling programmes. This made it possible to create a spatial vision of the pavilions, understanding potential functional and aesthetic criticalities. To this is added a further methodological deepening, in which parametric variations are made to the previously defined design using plug-ins (Grasshopper, Kangaroo, N-Gon), with the aim of supporting the simple, non-standardised and responsible development of the construction, fully implementing the principles of the complex circular economy (Fig. 4). In this case, the potential of these digital tools for the creation and optimisation of structural elements is exploited to the full, so that even complex organic shapes can be easily achieved (Fig. 5). Indeed, especially in the field of construction, parametric modelling tools allow designers to adjust several underlying parameters to explore a wide range of design outcomes [13], giving them the ability to sift through multiple solutions in less time and more efficiently.

3.3 Step 3

Once all the above criteria were met, the software returned to materiality, with the physical realisation of the shapes thus conceived through the technique of laser cutting first on a 1:3 scale and then, finally 1:1. The innovative charge of the proposed methodology lies both in its mechanical precision and in the speed of production of the desired components, which can be used as soon as the cutting process is finished. In the construction of the 1:1 scale pavilion, a single wall corrugated cardboard panel was employed, comprising a fluted corrugated sheet and two flat cladding sheets. The geometric dimensions of these panels were constrained by the material properties, specifically to prevent the production of excessively elongated

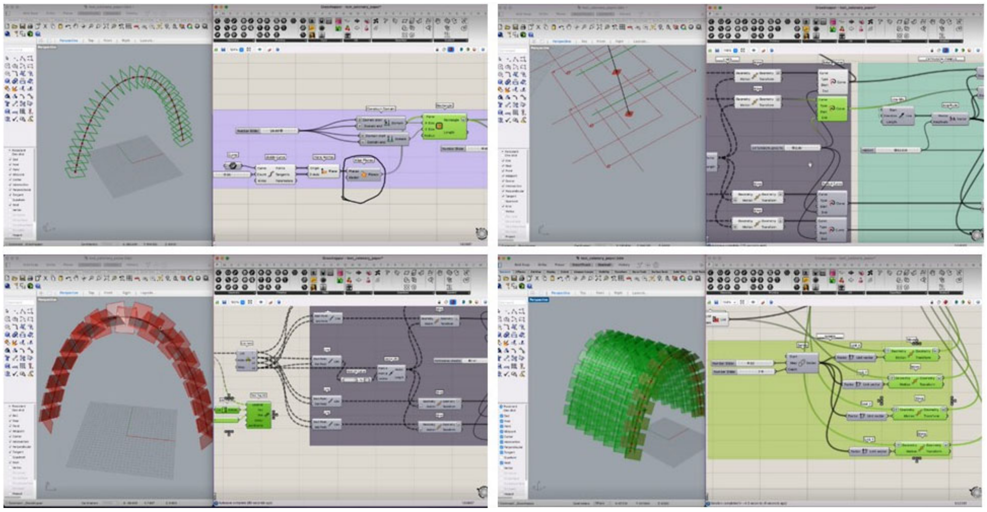

Figure 4: Designing with Rhino and Grasshopper.

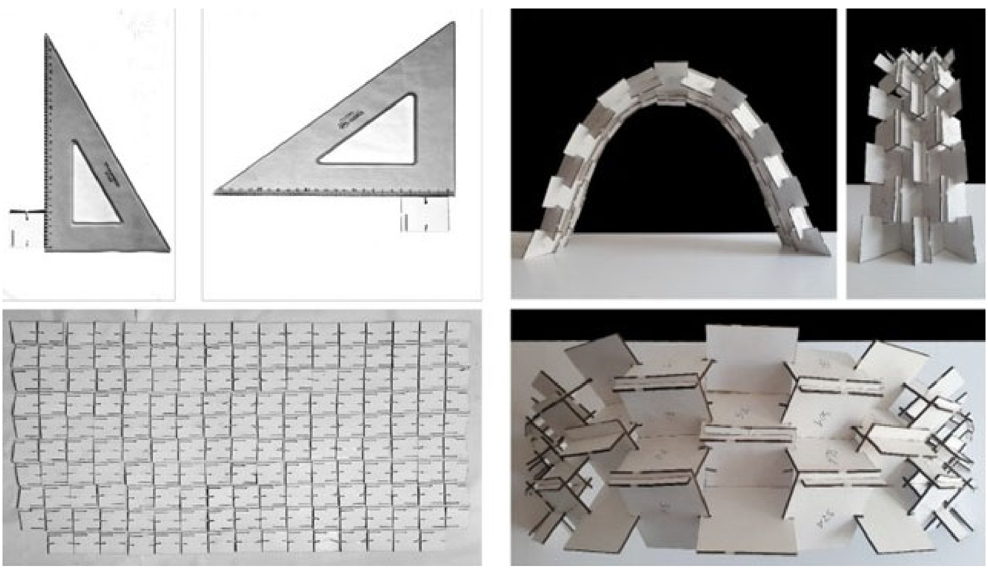

Figure 5: Optimised pavilion prototype.

elements that would compromise stability. An additional constraint arose from the specifications of the laser cutting bed, which limited the number of panels that could be derived from each sheet, in contrast to the smaller prototype models. Although this constraint led to increased fabrication durations, it ultimately yielded significant advantages by expediting the sorting and packing processes, thereby enhancing the efficiency of subsequent construction phases. If the steps just described are carried out effectively, the moment of physical construction of the pavilion prototype can take place simply by nesting the individual pieces made. The assembly procedure, in fact, adhered strictly to the numerical arrangement of the panels, thereby dictating the insertion sequence. A linear trajectory was established to link the components, commencing from the base and ascending in a spiral towards the apex of the shell. It was feasible to segment the sequence and execute multiple assemblies concurrently, whilst preserving the sequential integrity: initiating with a superior enumeration and progressively incorporating the series designated by the inferior enumeration. From a pragmatic perspective, the foundation and supports were initially positioned. Subsequently, in accordance with the sequential numbering of the labels, the edge-stiffened contour components, responsible for load transmission to the supports, were assembled. Adhering to the prescribed assembly order, the structure was constructed concurrently in multiple groups, which then unified along a singular assembly pathway to finalize the components (Fig. 6). The assembly process was executed efficiently: the entire structure was completed in under 15 hours by a cadre of students. In the course of this study, the students were exposed to digital design methodologies and a variety of visual programming tools, with a particular emphasis on the utilization of the physical simulation tool for shape exploration and component processing. Aside from digital modeling, physical prototyping enabled the recognition and analysis of subtle nuances in precision and tolerance, underscoring the critical distinctions between digital and physical models. While the testing phase utilizing scaled models provided a valuable educational experience, greatly appreciated by the students, the hands-on experience of constructing a full-sized structure proved to be even more transformative. The constraints of production, logistics, and material characteristics, exacerbated by the project’s scale, emphasized the significance of integrated structural reasoning and construction processes from the initial stages of designing complex architectural entities.

Figure 6: Portion of the archway of the pavilion under construction.

4 CONCLUSIONS

In an era of unprecedented environmental and social challenges, the technological reflection of architecture is called upon to rethink its paradigms and become a promoter of positive change. This study explored the potential of cardboard microarchitectures as an innovative and sustainable response to the redevelopment of interior spaces. Cardboard microarchitectures are constructions capable of responding effectively to the need for functional adaptations and, at the same time, devices capable of transforming the user’s perception, generating positive changes in the way space is inhabited. Indeed, human-centred manufacturing requires an emphasis on personalised and ‘tailor-made’ production, to ensure innovative growth in the manufacturing sector, while responding to the needs of individuals [14].

A growing urban population has, in fact, led to an elevated pressure on consumption of resources in cities. This further leads to significant structural waste and negative environmental impacts in the built environment sector. The need to change and redirect the concept of the transition to a circular built environment is key to achieving a resource-effective and sustainable society. In 2015, the United Nations General Assembly adopted the 2030 Agenda for Sustainable Development with seventeen goals, seven of which are directly related to the implementation of a circular economy. Innovations in the building and construction industry play a significant role in the development of sustainable cities and communities. In this sense, the type of structures designed using cardboard and practices related to parametric design can certainly open new horizons for the sustainable development of architectural environments. Cardboard is a lightweight material, yet it is notably strong and impact resistant. A study by Gribbon and Foerster [15] showed that, although cardboard panels do not have particularly remarkable water absorption properties, their thermal and acoustic performance is impressive compared to other high-performance products on the market. Furthermore, it is possible to design cardboard products with promising insulating properties. From an economic standpoint, cardboard is an affordable material, and its quality can be maintained even in mass production. Mass production and widespread availability are significant advantages for the construction industry, as they help reduce shipping costs. Lastly, the characteristics of cardboard reveal similarities to those of softwood, highlighting both its limitations and strengths.

The educational experimentations conducted demonstrated how cardboard microarchitectures can transform interior spaces, promoting a sense of well-being and connection with the environment. Their modular and reconfigurable nature makes them ideal for a wide range of applications, from temporary fitouts to collaborative workspaces, offering a sustainable and low-cost alternative to traditional constructions. It was described how, through a parametric design approach, it was possible to optimise the performance of these structures, maximising efficiency in the use of materials and minimising environmental impact. The choice of cardboard, a recyclable, low-impact material, proved to be a winner, allowing the creation of lightweight, flexible solutions that can be adapted to the different needs of users. Through this study and in-depth experience, we understand how it is necessary to systematically consider the approach to parametric microarchitecture as an opportunity for didactic experimentation and research, to obtain a new approach to the subject of architecture that can provide flexible answers in an increasingly complex world. Looking to the future, it is essential to continue to invest in the research and development of architectural solutions that integrate the principles of the circular economy and parametric design. Only through a holistic and interdisciplinary approach will it be possible to build a future in which architecture is at the service of man and the planet.

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