LORENZO SILVESTRI
965579

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SUPERVISOR
PATRIZIA BOLZAN

Material investigation on the possibilities to combine natural growth of mycelium and unfired clay for novel sustainable product design applications

TERRAFORMA

MASTER THESIS IN
INTEGRATED PRODUCT DESIGN

POLITECNICO DI MILANO
SCUOLA DEL DESIGN

POWERED BY
POLIFACTORY

Lorenzo Silvestri
mat. 965579

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Powered by Polifactory, Politecnico di
Milano’s FabLab and makerspace

To my parents, Agata,
Alessandro and Elia.

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ABSTRACT

ITALIAN

Il presente elaborato di ricerca si propone di indagare, attraverso una commistione delle pratiche progettuali della *Digital Biofabrication*, *Material Driven Design* e l'approccio *Do It Yourself*, le opportunità relative al campo di design di prodotto generate dalla combinazione dei materiali argillosi e quelli fungini. In particolare, l'investigazione si inserisce in un filone attuativo in cui emerge una nuova prospettiva legata alla figura del progettista stesso, capace - con le sue scelte - di far luce sul paradosso alla base delle dinamiche dei sistemi di produzione industriale e definire delle nuove modalità di intendere la materialità ed il rapporto con le risorse naturali e gli organismi viventi.

All'interno dello scenario contemporaneo, in cui il modello capitalista vede la tecnosfera alimentarsi a discapito della biosfera, fino a soggiogarla in logiche tossiche, emergono le contraddizioni di un sistema destinato al collasso che impone, ora più che mai, una fuga dai modelli di produzione tradizionali. La necessità di sfuggire alla forza gravitazionale esercitata dalle dinamiche antropocentriche, ha determinato la nascita di nuovi metodi per reperire, trasformare e preservare le risorse basati sull'implementazione dei processi metabolici degli organismi viventi. Affondando le radici in questa visione, questo lavoro esplora e impiega la Digital Biofabrication con il proposito di instaurare un rapporto collaborativo tra la componente umana, quella della macchina e quella degli organismi biologici. In questo contesto, il progettista agisce come facilitatore del processo di ideazione, sviluppo e produzione, mentre le tecnologie di fabbricazione digitale divengono un mezzo per guidare la crescita di materiali vivi verso il raggiungimento di specifici obiettivi progettuali.

Con questa premessa, *Terraforma* ha lo scopo di esplorare e dimostrare le possibilità applicative che si sviluppano nell'intersezione delle aree materiche dell'argilla greenware e del micelio in relazione ai processi di stampa 3D tramite Liquid Deposition Modeling, prima da un punto di vista della teorizzazione della loro compatibilità, poi attraverso un'investigazione sul campo delle fasi di fabbricazione, coltivazione ed assemblaggio coinvolte. L'output di progetto finale, un tavolino da caffè, viene proposto come una sorta di manifesto dimostrativo delle qualità materiche potenziali del materiale ibrido ottenuto all'interno delle applicazioni di prodotto, ma anche di una pratica progettuale matura, in cui i processi di fabbricazione e le logiche di assemblaggio sono a loro volta plasmati dai processi metabolici dell'organismo.

ENGLISH

This research paper aims to investigate, through a mixture of the design practices of *Digital Biofabrication*, *Material Driven Design* and the *Do It Yourself* approach, the opportunities related to the field of product design generated by the combination of clay and fungal materials. In particular, the investigation is part of an implementation strand in which a new perspective emerges related to the figure of the designer himself, capable - through his choices - of shedding light on the paradox underlying the dynamics of industrial production systems and defining new ways of understanding materiality and the relationship with natural resources and living organisms.

Within the contemporary scenario, in which the capitalist model sees the technosphere feeding at the expense of the biosphere, to the point of subjugating it in toxic logics, the contradictions of a system destined for collapse emerge that imposes, now more than ever, an escape from traditional production models. The need to escape the gravitational force exerted by anthropocentric dynamics has led to the emergence of new methods for sourcing, transforming and preserving resources based on the implementation of the metabolic processes of living organisms. Rooted in this vision, this work explores and employs Digital Biofabrication with the purpose of establishing a collaborative relationship between the human, machine and biological organism components. In this context, the designer acts as a facilitator of the ideation, development and production process, while digital fabrication technologies become a means of guiding the growth of living materials toward the achievement of specific design goals.

With this in mind, *Terraforma* aims to explore and demonstrate the application possibilities that unfold at the intersection of the material areas of greenware clay and mycelium in relation to 3D printing processes via Liquid Deposition Modeling, first from the standpoint of theorizing their compatibility, then through a field investigation of the fabrication, cultivation, and assembly phases involved. The final design output, a coffee table, is proposed as a kind of demonstrative manifesto of the potential material qualities of the hybrid material obtained within product applications, but also of a mature design practice in which fabrication processes and assembly logics are themselves shaped by the metabolic processes of the organism.

INTRODUCTION

The investigative efforts undertaken in this research strive to present practical solutions for the contradictions it addresses. Specifically, the exploration is directed towards an analysis of a context in which the role of design, specifically within the realm of product development, plays a pivotal role in steering the internal dynamics of social and environmental mechanisms influenced by human actions. In this context, design intervention leading to the creation of a product is intricately connected to a fresh interpretation of material resources and the formulation of sustainable solutions that envision collaborative efforts between the human species and other living organisms. Throughout the chapters, it will be referred several times to the final output as a demonstration object using the term manifesto. This word, the choice of which was not accidental, encapsulates two levels of interpretation related to two different areas of analysis of the process of investigation conducted, one related to materiality in the strict sense and the other related to the design practice through which this artifact will be fabricated.

One interpretation pertains to the innovative nature of the hybrid material resulting from the intersection between clay and fungal materials. As this is an essentially unknown field of investigation, especially when analyzed within the product landscape, its potential applications defined in relation to the material qualities that can be achieved are yet to be explored. The artifact in question represents only an exemplificative embodiment of the process of 'creating and materializing concepts' (E. Karana et. al, 2015) in which the transition from design intention to actual material/product realization takes place. The processes and activities necessary for the realization of the object are identifiable as fabrication techniques at the earliest stages of their existence, conceived in parallel with the verification of the soundness of the hypothesis of combination between materials. This therefore makes them on the one hand valid and verified only within the context analyzed and according to the methodology used, and on the other enables them to mutate and evolve in order to be perfected by other researchers seeking to advance their development. In this perspective then, the obtainable material specifications closely interconnected with possible alternative processes of design, cultivation and assembly and on the basis of which define the artifact, become an expression of the potential of this hybrid material for product applications, explored within the current investigation only in one of the possible declinations.

The second, more intricate dimension delves into the concept of 'becoming materials' (J. Bergström et al., 2010), as explored in the initial chapter, offering an all-encompassing interpretation of the process. This expression encapsulates the untapped potential inherent in all materials and elucidates how designers can harness this potential to forge novel design possibilities. In this context, a symbiotic relationship emerges within the realm of design, a dynamic interplay between the designer and the materials. While the human element and processes shape the materials, the materials, in turn, influence the choices and patterns of use, underscoring their role as active contributors to decision-making. The artifact produced at the culmination of this research thus serves as the embodiment of specific decision-making and technical processes integral to the codification of the final output. Simultaneously, it serves as a broader manifestation of the dialogue established among humans, mycelium, and technologies. In this context, the object is to be comprehended as a manifesto of a distinct design approach, stemming from the convergence of *Material Driven Design*, *Digital Biofabrication*, and *Do It Yourself*, which collectively orient the entire methodology. Viewing the output through this lens reveals it as a physical manifestation both shaped by and a shaper of the orchestrated design practices conceived to exploit the organism's metabolic processes.

The reflections outlined above, coupled with the issues and contradictions elucidated throughout the entire thesis—particularly concerning the analysis of clay materials, the unsustainability inherent in anthropocentric and neoliberal models, and the pivotal role played by digital fabrication technologies—culminated in the conceptualization of the term *Terraforma* after which the final artifact is named. Specifically, this term offers a semantic recall of the multiple themes addressed during the research. Primarily, it resurrects the term terra, the italian equivalent of "soil" used to refer in a deliberately generic way to the raw clay, the undisputed protagonist of the research around which the entire material investigation revolved. It aims to emphasize the natural component of a resource so commonly found on our planet and yet so violently transformed by man-made processes to the point of making it a resource that can no longer be reused. Secondly, Terraforma places the focus on the role of digital fabrication which, employed in conjunction with living organisms through Digital Biofabrication, drives a process of 'shaping' the material aimed at 'extracting' its hidden potential which is metaphorically opposed to the process of physical extraction and uncontrolled exploitation of resources. Moreover, the term draws a direct connection to the concept of *terraforming*, defined as the process of artificially altering the environment of the moon or a third planet with the objective of rendering it suitable for human habitation. This involves intervening in the atmosphere to make it resemble that of Earth, capable of sustaining an ecosystem (Cambridge Dictionary, 2023). Despite sharing the root, however, the two words in question are meant to express diametrically opposed views. Terraforming, as conventionally understood, embodies a paradigm where the quest new habitable worlds to be colonised underscores the failure of the anthropocentric model on our very planet. Conversely, the vision proposed in the research aligns with an alternative narrative, viewing the 'escape', from the gravitational pull of Anthropocene logics as theorized by Caffo (2022), in a positive light. Here, 'escape velocity' represents a shift and a departure from the set of practices and the way of considering resources that have brought the planet, and with it all life forms that inhabit it, to a point of collapse.

The current material investigation, culminating in the fabrication of a physical artifact, is therefore intended to propose concrete resolutive models of the contradictions exposed within it. Terraforma seeks to serve as a manifesto, highlighting the responsibilities and possibilities inherent in the design practices with which we choose to shape the environment we live in every day. Terraforma tells about a vision of progress that departs from the one traditionally associated with this word, it tells about a possible reality in which materials have the power to positively influence our choices and at the same time in which our species is called, once and for all, to orient the future toward sustainable practices.

The first chapter delves into a comprehensive analysis of the landscape within which designers operate, marked by neoliberal dynamics stemming from the dominance of the economic production apparatus at the expense of ecosystem balances. It underscores the contradictions of the anthropocentric model and advocates for a coherent and critical design approach to address contemporary challenges. The chapter proposes alternative visions opposing capitalist cultural, economic, and productive orientations, emphasizing creativity, sustainable innovation, material experimentation, and open-source principles. It explores DIY ethics, maker culture, and BioDesign, with a particular focus on Digital Biofabrication. Within this context, materials are introduced as intelligent entities fostering a co-design relationship, and the designer's role as a facilitator of the dialogue between humans and nature is emphasized.

In contrast, the second chapter centers on the exploration of clay materials from various perspectives. It highlights the sustainability of working clay in its greenware state versus the environmental impact of thermal processes transforming it into ceramics. This discussion leads to the consideration of a new class of materials, UBWCCS, comprising a raw clay matrix and an organic dispersed phase, ensuring complete biodegradability and aligning with circular practices. The chapter envisions a novel scenario in product design related to these materials and their integration with digital fabrication technologies.

After exploring traditional clay, the third chapter shifts focus to materials derived from living organisms, specifically mycelium, the filamentous network responsible for fungi's digestive system. It introduces MBCs, innovative materials produced through the organism's metabolic processes by degrading organic bases. The exploration initially centers on understanding the manufacturing processes of MBCs through various cultivation techniques. The chapter then discusses strategies for tuning the material properties of MBCs, considering design interventions in the fungal strain, substrate, and manufacturing processes.

The fourth chapter extensively explores the manufacturing processes of fungal composites, showcasing relevant case studies. This section primarily emphasizes design strategies employed by the designer to influence the organism's growth, achieving specific material qualities and guiding its development to meet specific design objectives. Simultaneously, it delves into the reciprocal relationship—examining how the mycelium's growth requirements shape processes and how human interventions strive to strike a design compromise between manufacturing technologies and the organism's proliferation.

Shifting to the fifth chapter, it focuses on theorizing the synergy between clay and fungal materials, highlighting the innovative aspects they can collectively generate. The narrative reflects on critical issues associated with UBWCCs and proposes an inventive approach, positioning mycelium as a central element in addressing these challenges. Additionally, the chapter introduces Material-Driven Design (MDD), a design practice that prioritizes the specific material as the genesis of the design process, exploring and understanding its qualities before defining the design output (E. Karana et al., 2015). The chapter provides an overview of the current state of the intersection between the two composite materials, analyzing relevant case studies. Through this exploration, a knowledge gap regarding the combination of clay and mycelium becomes apparent, leading to the identification of specific design objectives for investigation in the subsequent material testing phase.

The sixth chapter transforms the material investigation into a field-based research endeavor, exploring various process segments such as cultivation, fabrication, and assembly of the artifacts. This section delineates an experimental methodology, categorized into four areas of interest. These include the initiation of fungal culture, preparation of necessary equipment, familiarization with MBCs, and the fabrication of samples using LDM fabrication technologies. The chapter concludes with reflections on the acquired knowledge and an exploration of constraints and opportunities that inform the final research output.

Moving to the seventh and final chapter, the focus shifts to the fabrication of the ultimate prototype. The selection of the object type for fabrication follows a practice of artifact codification, characterized by a systemic organization of design protocols and the formulation of qualitative specificities integrated into the physical output. This practice aims to establish clear guidelines and instructions for designing geometries, their fabrication, cultivation, and assembly. Building on the insights from the sixth chapter, the final artifact is defined. The concluding section recounts the prototyping process and details the design strategies employed to overcome challenges encountered during the field investigation.

The thesis concludes with a critical analysis of its outcomes, providing a summary of the results and objectives achieved in material exploration. Considerations are offered regarding the potential developments of the hybrid material resulting from the combination of clay and mycelium composites.

BIBLIOGRAPHY

Bergström, J., Clark, B., Frigo, A., Mazé, R., Redström, J., & Vallgårda, A. (2010). Becoming materials: material forms and forms of practice. *Digital Creativity*, 21(3), 155-172.

Caffo, L. (2022). Velocità di fuga (1a ed.). Torino: Giulio Einaudi editore.

Cambridge Dictionary [Online]. Available at: https://dictionary.cambridge.org/dictionary/english/terraform Accessed (23 November 2023).

Karana, E., Barati, B., Rognoli, V., & Zeeuw Van Der Laan, A. (2015). Materiai driven design (MDD): A method to design far materiai experiences. International journal of design, 9(2), 35-54.

Karana, E., Nimkulrat, N., Giaccardi, E., Niedderer, K., Fan, J. (2019) 'Alive. Active. Adaptive: Experiential Knowledge and Emerging Materials', *International Journal of Design*, 13(2), 1-5.

"Non fatichiamo, come ovvio, a vedere il progresso nell'immagine di Dubai e una sorta di affascinante primitivismo in quella degl insediamenti Yanomami e a mettere in correlazione il modello Dubai con i dati che portano alle proiezioni del 2050, mentre il modello Amazzonia ci appare perfettamente compatibile con un ancora lungo periodo di vita per Homo Sapiens sul pianeta Terra. Non si tratta di far propria un'argomentazione strettamente primitivista ma di andare, per logica, a testare modelli risolutivi dell'enorme problema che questo secolo dovrà affrontare tra pandemie, catastrofi climatiche, incapacità di reggere la ridistribuzione alimentare per dieci miliardi di persone. Molti dei miei studenti per cui ho formulato questa analisi per la prima volta studiavano per fare gli architetti o i designer, dunque la palla passa sicuramente alle loro mani piuttosto che alle mie: quali strumenti, quali luoghi, quali materiali potrebbero permettere un approccio integrato tra il tentativo di imprimere visioni di mondo tipicamente umano-occidentale, come quella che ha portato a Dubai, e il vivere aderenti al mondo dei nativi?

Qui serve tutta la nostra energia intellettuale, questa non è una sfida come un'altra e qui la fuga si consuma in positivo o in negativo e l'unica cosa che non sarà possibile è la stasi."

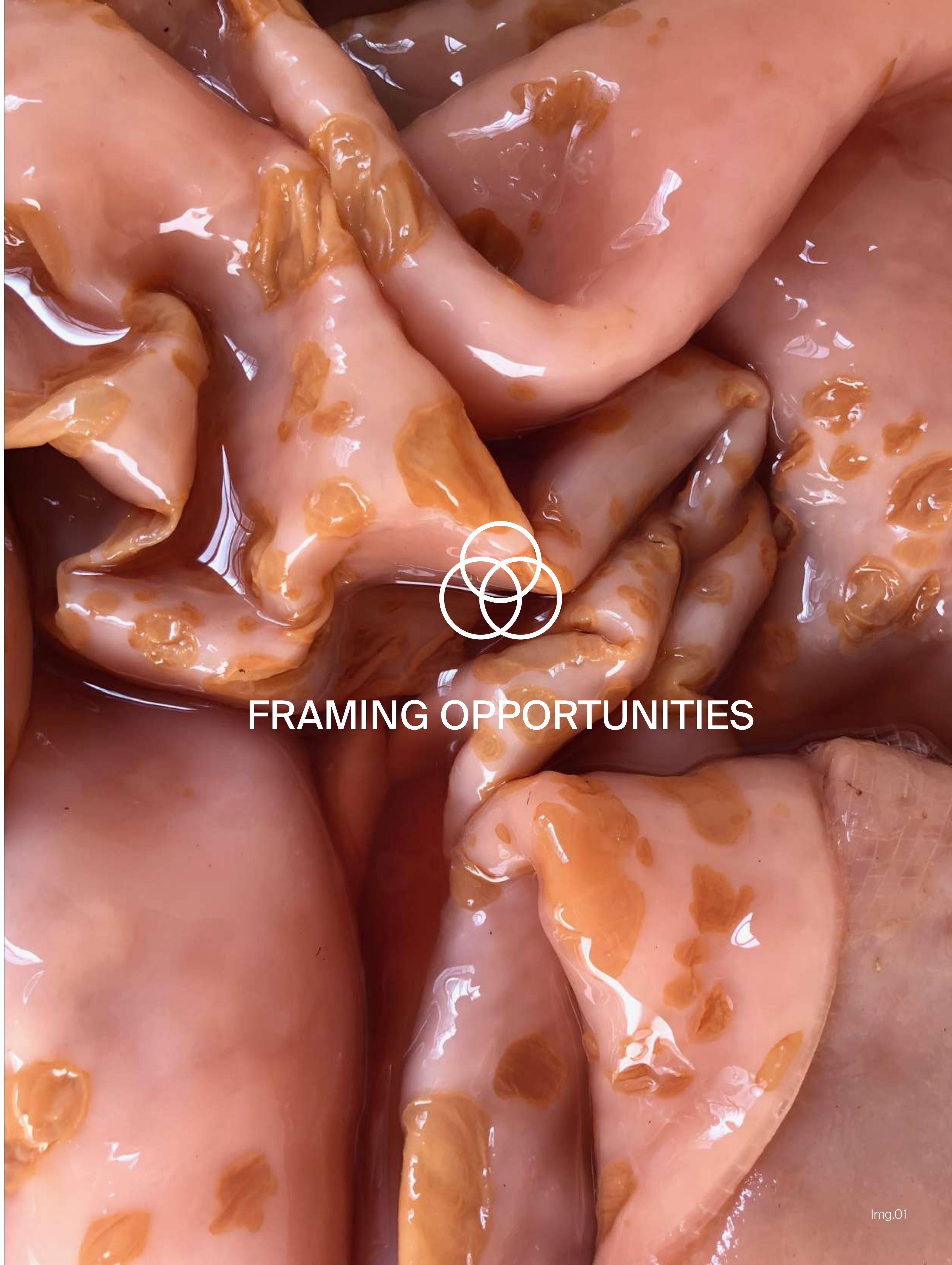
Leonardo Caffo, Velocità di fuga, 2022

CHAPTER 1

1.1 ON THE NEED TO BRIDGE THE GAP

1.2 AT THE INTERSECTION OF FUTURES

... Within this scenario, the role of the designer plays a crucial role, that of the mediator and facilitator of the entire process. The designer collaborates with nature and machine to achieve specific design goals in which products are complex constructs of living tissue. Specifically, he is responsible for creating and developing a system in which digital tools and biological structures are compatible, ensuring that the design is optimized for functionality and meets required biological specifications. The complementarity of human action and nature's work, supported by advanced fabrication methods, gives this practice extraordinary potential that is still largely unexplored. Today's and future's designer must therefore adopt a design perspective that conceives of materials as intelligent agents that behave adaptively with respect to their environment, the same he finds himself designing and shaping and at the basis of which the dialogue between nature and designer takes place ...



FRAMING OPPORTUNITIES

Img.01

ON THE NEED TO BRIDGE THE GAP

1.1

1.1.1

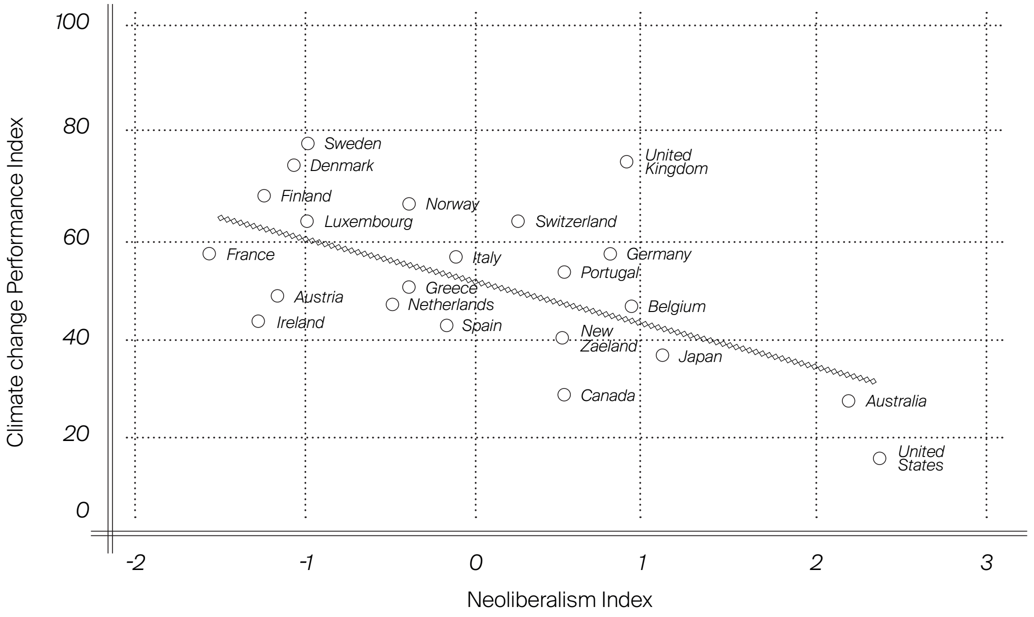
The paradox of contemporary design

The term *Anthropocene* refers to the current geological epoch in which human activities have caused spatial, structural, and climatic changes that can directly affect geological processes now and those to come (D. Carrington, 2016). Our species is more than just a gear in the delicate ecosystem balances that govern the Earth, which now finds itself compromised by processes triggered by human actions. In conjunction with the development of human evolution, and particularly during recent centuries, there has been a very rapid loss of biodiversity when compared with natural cycles that usually take thousands of years, if not millions, to generate the same kind of dynamics. In the last few decades alone, there has been a consistent decline of every animal species, with peaks where half of the existing species have lost about 80% of their range. This process in which billions of mammals, birds, reptiles and amphibians are gradually disappearing into extinction is a process that has been going on for some time, the effects of which are only now becoming frighteningly visible. Habitat destruction, overhunting, introduction of alien species, and land consumption are driving a process known as the *sixth mass extinction* that will soon lead to the disappearance of about 75% of living species (D. Carrington, 2017). Human overpopulation, furious rates of consumption of nonrenewable resources, emissions of harmful substances into the atmosphere, loss of biodiversity, deforestation, pollution of the seas, and poor waste management are among the most obvious causes of the most rapid climate change in the history of the planet. For about two centuries, in conjunction with the industrial revolution, human actions have begun to generate dynamics that have profoundly altered ecosystem balances bringing them extremely close to a point of non-reversibility and the collapse of the planet.

The Earth has already overheated by 1.2 C° compared to the pre-industrial era, and the United Nations Intergovernmental Panel on Climate Change (IPCC) estimates that the only way to contain the temperature rise to within 1.5 C° is to reduce net CO2 emissions by 45 percent by 2030 and eliminate them by 2050 (A. Fremstad et al., 2022). As of today, to say that the planet was greener before the era of industrialization seems almost taken for granted, but it is only since the 1980s that global temperatures began to rise at an alarming rate. The cause of this phenomenon must be sought in the economic mechanisms that took hold during those years and that affected both the environment and society. The advent of neoliberalism, which quickly became the dominant economic force in Western society, led to a commodification of the planet's resources and helped shape a market concept in which production does not take into account the Earth's capacity to regenerate natural resources. Moreover, the neoliberal vision implies that people are cogs that respond to the economic forces that regulate the system rather than active parts of it that should help actively shape the economic scenario. Citizens, transformed into consumers pursue individuality through consumption, and this fuels competition among industrial actors that legitimizes resource exploitation in the name of profit and efficiency (M. Greenwood, 2021).

To achieve the set goals of containing global warming to acceptable levels, the entire economic apparatus will have to shift toward a direction in which production will not have to be profit-driven. Within this scenario, natural resources will not be considered property at the service of humans to be extracted at will, but rather something to be stewarded in a non-exploitation relationship established between us and the planet itself. The authors, Anders Fremstad et al. (2022), identify three ideological principles of neoliberalism that have contributed to climate policy inaction: decentralization of democracy, cutting public investment, and deregulation of the economy. (1) The decentralization of democracy is the result of subjugating the state to neoliberal market forces. Such logics promote competition among political jurisdictions instead of operating through solidarity principles, and the result is climate action with reduced effectiveness. Addressing the climate crisis requires the implementation of international policies but the costs of actions aimed at curbing emissions are local even though the benefits they generate are global. (2) Cutting public investment, on the other hand, is a further consequence of the spread of neoliberal principles within the political arena. Such ideologies have displaced the state

Img.02
Neoliberalism and climate change performance across countries. The Climate Change Performance Index quantifies performance based on countries' emissions, energy use, renewable energy, and climate policy. The neoliberalism index is constructed as a sum of three z-scores based on the three tenets of neoliberalism highlighted in Anders Fremstad et al., 2022: decentralization of democracy, cutting public investment, and deregulation of the economy. The Analysis is restricted to high-income countries. Grapich redesign of the scheme in Anders Fremstad et al., 2022.



from its role as provider of public services, stabilizer of the economy, and solver of coordination problems. Policy subject to capitalist principles, operates simply according to the interest of profit with public investments that are often avoided because of their costly nature. (3) Finally, neoliberal logics have eroded the ability of the state body to regulate the economic scenario through regulations. They are not seen as useful tools for shaping markets, but instead represent *bureaucracy* that increases entrepreneurial costs and weakens the economy.

In this economic and behavioral system that human beings have built around the *technosphere*, the designer finds himself operating in a context that has generated an internal fracture in his professional figure. An industrial perspective and one aimed at the social appear disconnected, opposed and unable to coexist. Such a split brings to light the inadequacy of the current conception of the designer's role, considered as a cog in the capitalist system with the ultimate goal of fitting in and adapting to market logic. The term *neoliberalism* refers to a political-economic thought born in the 1980s on which the principles governing capitalism are based. George Monbiot (2016) writes that "[...] neoliberalism sees competition as the defining characteristic of human relations. It redefines citizens as consumers, whose democratic choices are best exercised by buying and selling, a process that rewards merit and punishes inefficiency. It argues that the market offers benefits that could never be achieved by planning." In simpler words, today's economic-social fabric is based on inequalities, it feeds uninterruptedly on them because it needs them to survive. Within this scenario, design, and in particular the figure of the industrial designer, is often a piece of this puzzle whose role is to design so that market logics do not get jammed and inequalities continue to recur and emerge ever more sharply. Arturo Escobar 2018 (in M. Sloane, 2019, p.5) tends to see design as both the cause and the cure behind the ecological and social crisis of our time. This approach to the subject pushes the figure of the designer to question what his or her role and duties are in society and, as a result, raises questions about the current context in which the design profession must forcibly find itself operating. If we assume as true that "[...] we design our world, while our world acts on us and designs us" (A. Willis, 2006, p.70), it seems essential to heal the internal rift in this figure in order to think about fighting a system that feeds on the very inequalities it generates. Such a large and complex scenario, subject to delicate economic and political mechanisms, requires a deep and intimate reassessment of the profession and morals of the designer that must necessarily start from the bottom, with an awareness of one's role in the eyes first of all of oneself and consequently of society. The education of conscious professional figures, occupies a fundamental role in this regard. The discussion begins by addressing the difficulties of the designer in operating within the current industrial environment, which prevents him from following a socially oriented ethic. As a result, society finds itself bewildered and deceived by market logic. Possible solutions related to the creation of systemic apparatuses, infrastructures and networks within which he operates as a public mediator are thus brought to light. In order to make this possible, however, the starting point must necessarily be personal, according to a view that sees the figure of the planner questioning himself in order to be able to reclaim his role in the community and to be able to prepare it for change before offering himself as a bridge between it and the industrial apparatus. His education, in the broadest sense of the term, represents the only way to acquire a design philosophy that can free him from the paradox of having to design for a market that is a slave to consumerism, which, with the intention of making the environment around us more and more comfortable has ended up destroying the only real environment that we live in.

^ Img.03, 04
^ Anthropocene, Untitled. Illustrations by Justin Valdes.

1.1.2

Redesigning ourselves

"I designer sono i primi tra i miei nemici. Il 95% è totalmente ignorante. Sono dei piccoli robot che accettano come valore solo il mercato. Poi c'è un 5% che capisce, ma cinicamente accetta le distorsioni dello stesso mercato: oggetti costruiti solo per durare qualche mese [...] Non servono a chi li acquista ma a chi li produce per fare profitto. E' legittimo, ma non si riempiano riviste e volumi per dire che questi lavori contengono qualcosa di cui la società ha bisogno [...] Il problema è che oggi tutti i grandi imprenditori realizzano oggetti solo per produrre denaro."

[Designers are the first among my enemies. Ninety-five percent are totally ignorant. They are little robots who accept only the market as their value. Then there is a 5% who understand but cynically accept the distortions of the same market: objects built only to last a few months [...] They are of no use to those who buy them but to those who produce them to make a profit. That's legitimate, but don't fill magazines and volumes to say that these works contain something that society needs [...] The problem is that today all the big entrepreneurs make objects just to make money].

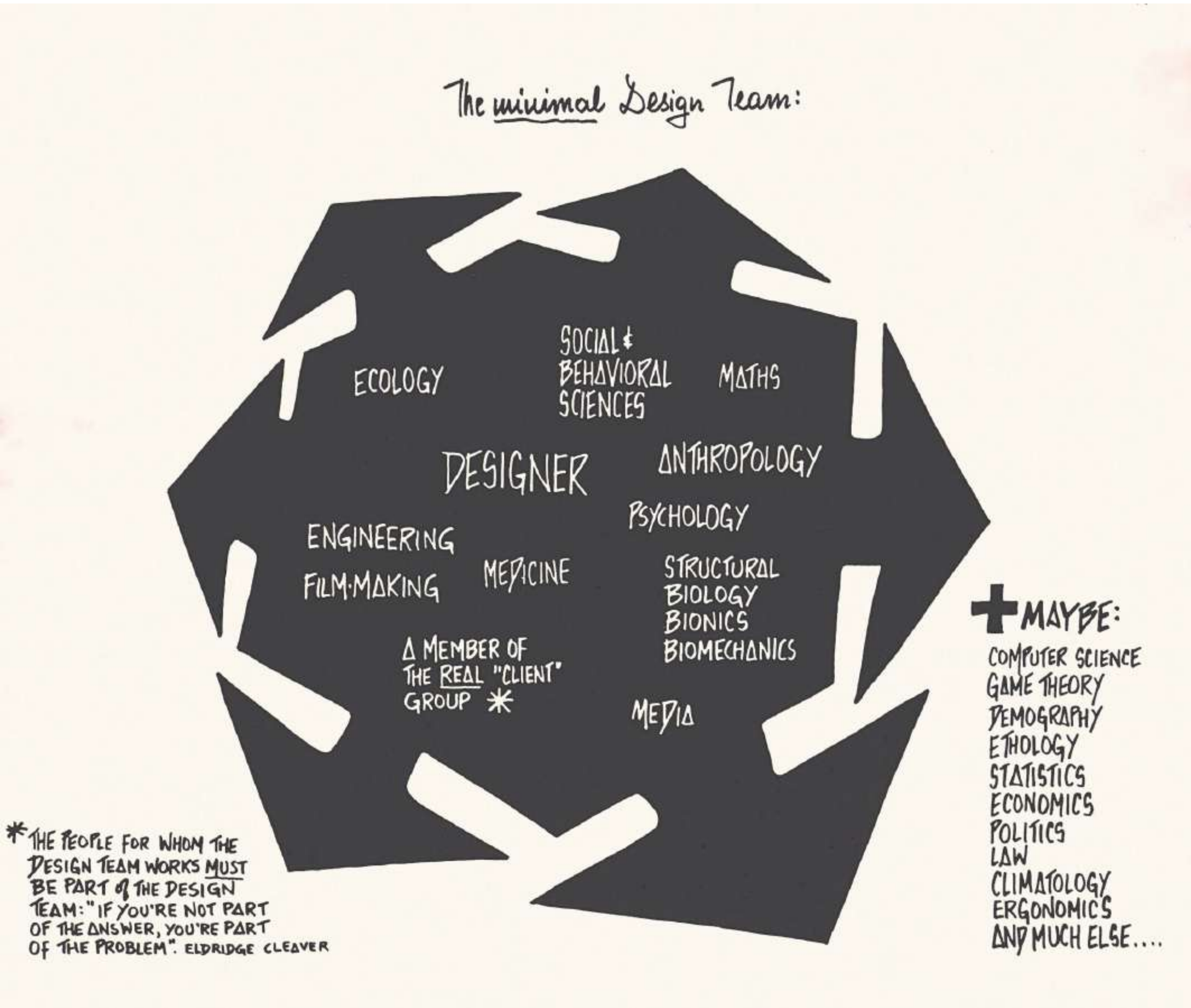
With these words, Enzo Mari (in V. Zincone, 2011) offers a critical picture of the situation, still relevant today, affecting the world of industrial design and, by extension, designers as well. The limbo in which society finds itself, at the root of the rift that sees designers unable to overturn their role within it, is perfectly described. By these laws of the market they are crushed, forced to adapt in order to carry on the profession that, by definition, consists precisely in designing objects that must be sellable on a large scale to generate monetary value. Here arises the contradiction that fuels the entire system and takes the problem to a broader level: these products are created for the purpose of financial gain and not to solve real needs, cutting out of this equation the responsibility of designers to bring, through them, social welfare. Moreover, as Nicola Morelli (2007, p.5) observes, the continuous introduction on the market of objects capable of solving the simplest everyday needs has led to a *passivization* of the user who, relieved through them of difficulties, becomes increasingly dependent on them, no longer being able to distinguish which are his real needs from those imposed by the market. In the same way as the designer, he too thus becomes a cog in this self-powering machine.

In addition to the more explicit problem of designer-industry dynamics, there is thus the problem of a society strongly stunned by their consequences, which is unable to protect itself and needs a figure to guide it. This middle figure between the market and consumers necessarily resides in the designer, potentially able to show and direct what are the actual needs that the community needs to solve in order to achieve a social balance constantly threatened by modern economic logic. The determining component of the current industrial context that makes the cycle continuous and dead-end is the inability on the part of designers to achieve an ideal of *pure design* (V. Papanek, 2019), in which a neutral morality in the designer materializes only when he or she operates untethered from the market, addressing the social accordingly. This notion of the consolidation of the profession linked to society has been explored by other authors who have analyzed a changed economic and political context since 1971, the year of the first edition of Papanek's book "Design for the Real World: Human Ecology and Social Change." There is a growing demand for the designer to reclaim his or her social role in the scenario of neoliberalism, which, by definition, seeing the intrusion of the state into economic mechanisms as negative, consequently tends to offload these social responsibilities to extra-governmental bodies such as NGOs, private agencies, religions, etc. Guy Julier and Lucy Kimbell (2019) state how designers nowadays are redesigning complex systemic apparatuses, but that because of the way their professional figure is conceived, they are not yet able to redirect the inequalities that result from these interventions. In fact, since they are figures outside institutional logic, they often see their interventions jammed into the bureaucratic machine and prove to be only *virtual* and distant from reality. They therefore propose to break down the "designer-client dualism" through a long and difficult work of policy implementation, in which designers are public figures, politicians, public employees so that they can have knowledge of the context in which they operate, intervene in the processes that generate inequality and be accountable to society for their actions. In the opinion of Nicola Morelli (2007) instead, it is necessary to reconfigure the industrial environment so that it is able to solve problems at the local level: industries should solve problems not through finite solutions but by creating an organizational network in which various figures at different levels act as *co-pro-*

ducers of solutions. Designers in this context would design scenarios, platforms and operational strategies to enable users to co-produce these solutions. Their participation, understood not as that of passive consumers but rather as resources in the process, would drive the economy to be based on real needs properly recognized and framed by end users, and also toward a more conscious use of resources.

The solutions just seen, are based on a systemic organization that involves the collaboration of different actors at all stages of the process starting from design, through production, distribution, regulation and finally user use. In addition to a complex organizational system of resources, such a process to be sustainable requires as a final condition the presence of a mature society that is aware of its role within the market gears. This prerogative is one of the pillars underlying these solutions and, for the same reason, often determines its failure or impossibility. However, as described in the previous section, it finds itself disoriented and unable to be part of this change. John Dewey 2012 (in K. Hansson et al, 2018, p.4) defines as fully formed “an audience when its constituent individuals are aware that certain forces and consequences affect them collectively and when they have the means to recognize and communicate this collective” Therefore, the challenge for designers of this time becomes to ensure that society achieves this awareness of being a fundamental part of the process of change, a prerequisite for taking an important step toward the abatement of system-generated problems.

Jorge Frascara (2007, p.68) writes that “to be a good designer in the broad sense of the term, in addition to technical knowledge, one must be a good citizen, which is a socially responsible person.” The designer is inherently proposed as a figure in whom multiple approaches to reality coexist including technical, humanistic, creative etc. This blending of different skills, backgrounds and perspectives often results invisible to the eyes of not only consumers but the entire production apparatus, relegating them to mere aesthetic curators of society’s whims. As seen above, however, its role is instead quite different if it remains hidden from the eyes of the many, crushed by the logic of the market. By dint of being continually subjected to this oppression, however, designers have also lost the value and goals of their own profession, which precisely because of this invisible component falls into what John Howkins (2020, p.61) calls the *Fourth Circle*. Creating a division into four groups based on different approaches to work, in which each has a different view of the world, the author includes in the latter those whose specialty is to “change people’s perceptions of people or something, or to change people’s perceptions about their perceptions of things”. These observations about the intimate components that define such figures perfectly frame a profession as fluid as that of the designer who, precisely because of them, is and must be capable of redesigning himself as well. It is therefore necessary first and foremost that he or she process a personal change before reflexively bringing one to the community. Such a change starts with gaining an awareness that it is precisely at the basis of his own choices that inequalities begin. He must adopt a philosophy in which designing for the marketplace and designing to solve needs coexist under a single denominator, with the lucidity to devise solutions to real problems where his intervention can truly be the bringer of change. And paradoxically, this change is demanded by the vast majority of the population given the problems of the modern age such as the climate crisis we are all facing. From the height of society’s elitist artist role for the designer, it seems too easy and convenient to mistake for a majority what is actually the minority for whom he or she produces. This mind-set of the designer and his ability to critically observe reality are the first skills he must rediscover so that the value of his work does not fall on deaf ears. Such a design approach is the first step to be taken because it can slowly break through from within the complex economic mechanisms that govern neoliberalism. In doing so, not only will a first step be taken to generate social welfare where it is really required, but a concrete foundation will be laid for individuals to be enabled to understand their own value within the collective dynamics. This vision of a conscious, healthy, and self-possessed society is echoed in the words of Geraldine Fraser-Moleketi (in Staff Reporter, 2011) who states that “people are the real wealth of nations. Development therefore means expanding the choices that people have to lead lives that they value. And it is therefore about much more than economic growth, which is just a means-though a very important one-of expanding people’s choices”.



^ Img.05
The minimal Design Team, section of illustration in the “Big Character” Poster No. 1; Work chart for designers from “Design for the Real World”, 1973, Victor J. Papanek.

In order for the young designers of the future (and of the present) to acquire this design philosophy that sees industrial and social perspectives coexisting (or more appropriately, to acquire an industrial perspective aimed at the social), it is necessary that their education is not merely a sterile training, but is steeped in these principles. Unfortunately, current design-focused educational programs rely too little on these, contributing to shaping professional figures crushed by economic mechanisms both because of the context and their thinking *trained* to match them. Again Papanek (2019, p.287) asserts that “education is a process in which the environment changes the student, and the student changes the environment” assuming precisely that the environment is something non-static that can itself be shaped. But the second part rarely finds foundation in reality. Despite this assertion, educational methods still prove to be too unresponsive to the fast-emerging changes facing modern society, so much so that many of the problems Papanek addressed 50 years ago are highly relevant today. The lack of direct exposure to different concrete design philosophies, in favor of adherence to theoretical methods preset on industrial logics, prevents students from developing critical capacity and their own design identity that can lead to real change and is one of the causes of this standardization of their thinking. Making this confrontation more direct, but above all more fruitful in terms of personal growth and diversification is a fundamental step to allow, from the very beginning, the designers of the future to glimpse and develop alternatives to the conformation rules dictated by the economic system.

We have analyzed how the current economic scenario pushes the designer to bend to its logic in order to pursue his profession, leading to a rift in his identity between industry and society. An overview of this context is necessary to place the figure of the designer within it, exploring specifically the contradictions that animate him. The consequences they have both on himself and on a collective that shows itself equally incapable of pulling itself out of them, impose a reflection on what should be the principles and objectives of a profession, that of design, characterized by a still too limited social sense. Certain types of systemic solutions that would elevate the designer’s role to that of a public mediator between industry and society require that it be mature and aware of its role within these scenarios. It thus becomes the designer’s task to empower individuals to embrace these types of changes, but this can only be done through a reevaluation of its role by itself, with a redesign of its morals and identity. In order for the community to achieve a balance of well-being, the designer’s task becomes in this sense to solve types of problems that can truly bring about change. Only by focusing on these kinds of needs will he be able to take back his role and build a society ready to deal with the problems of this age, among them the environmental one. Therefore, the role of education in the profession, which must be subjected to social challenges as much as possible, turns out to be central. This must be made possible by direct exposure to different design philosophies and approaches to the discipline already in education, which can enable diversification of the new designers of the future and make them capable of developing an autonomous line of critical thinking that reasons outside sterile industrial schemes. For something to move, the concept of industrial design should be inextricably linked to that of social design and should operate as a single vector of change, through a process that must begin with the rediscovery and transmission of collective values to new generations. This last point represents the key factor capable of healing this rift and developing a social sensibility in the profession that needs now more than ever to free itself from the traditional economic logics of consumerism.

AT THE INTERSECTION OF FUTURES

1.2

1.2.1

DIY, Maker culture and Fablabs

However, despite the scenario just described, there is a gradual emergence of environmental practices and shifts in both individual and collective behaviors, presenting alternative visions for the future. This growing consciousness is underpinned by advancements in science, increased awareness of environmental issues, and a pursuit of sustainable production and consumption models aligned with the principles of the circular economy. This shift in human dynamics, moving away from purely economic practices towards ecological considerations, necessitates not only a transformation in our intangible cultural values but also a significant evolution in our material culture. In recent years, there has been a heightened emphasis on optimizing finite resources and the rise of innovative, non-polluting, and biodegradable materials. These new materials, often derived from plant sources, harness the advancements in science and the interdisciplinary knowledge accumulated by scientists, engineers, and designers to mitigate the environmental impact associated with conventional materials. In tandem with advancements in the field of materials, there has been a noteworthy rise of the *Do It Yourself* (DIY) ethic in recent decades. The term DIY encompasses an approach to hands-on creation, design, construction, modification, and repair that does not require one to be a professional to undertake a specific task (S. Kuznetsov & E. Paulos, 2010). At its core, DIY celebrates the significance of the creative process, drawing inspiration from tradition, craftsmanship, and alternative production techniques that diverge from the industrial models of neoliberalism.

The DIY ethic, particularly within a technological context, has been embraced by a diverse collective of individuals who share a common vision that opposes the cultural, economic, and productive norms of capitalism. This movement, often referred to as the *maker culture*, represents a technological embodiment of the DIY principles. Emanuele Toscano (2022, p.2) characterizes it as a “socio-material and organizational expression of an emerging and thriving culture characterized by elements of creativity, innovation, experimentation, and hands-on learning”. Originating in the United States, the maker model has rapidly proliferated globally thanks to the democratization made possible by the widespread availability of digital fabrication technologies. This expansion has been facilitated by social networks, platforms, and online sharing

Img.06
MYX chair by Jonas Edvard, 2020.

spaces where communities of individuals converge to create and disseminate projects, knowledge, manuals, and tutorials, providing peer-to-peer support for individuals with varying levels of expertise. From this perspective, the maker movement embodies a set of inspirational values centered on open-source production and distribution (emphasizing open sharing, cooperation, and free distribution) and a design philosophy rooted in free learning and creativity (S. Kuznetsov & E. Paulos, 2010). In line with this, Emanuele Toscano (2022) asserts that makers, through their use of technology, aspire to "construct a sociotechnical system—a network of human-object relationships or a nexus connecting individuals, institutions, and objects". The same author characterizes the maker movement as a variant of a social movement, which is a type of collective endeavor distinguished by several features: firstly, it exhibits an organizational structure in which individuals collectively form identities and forge bonds of solidarity (C. Tilly in E. Toscano, 2022). Secondly, it encompasses a series of practices aimed at challenging the prevailing values, cultural norms, social structures, and economic paradigms of contemporary society, often competing with dominant actors (M. Castells in E. Toscano, 2022). Lastly, it involves the generation of knowledge with the intent of catalyzing social change, with the capacity to translate this knowledge into political action (R. Eyerman & A. Jamison in E. Toscano, 2022). Within this analytical framework, the maker movement can be situated as an entity that "orchestrates collective actions contributing to the promotion of a new interpretation of sustainability (via reusing and repurposing technological waste), learning (through the utilization of advanced digital production technologies), and simultaneously intervenes in reshaping the cultural, economic, and social orientations of society by advocating for alternative modes of production and consumption, fostering creativity, sharing, and social interaction" (p. 8).

The remarkable expansion of the maker movement can be attributed to a distinct factor that has played a significant role in its widespread adoption and practice: the emergence of *Fabrication Laboratories,* (Fab Labs). This term denotes community spaces dedicated to digital manufacturing, where individuals from diverse backgrounds such as designers, inventors, professionals, educators, and digital artisans come together to exchange expertise, share ideas, and collaborate on projects characterized by digital manufacturing techniques. Fab Labs form a dynamic global network, with most of them actively engaging in collaborative efforts to develop and disseminate projects and knowledge. At the heart of the Fab Lab concept lies a profound social principle: to establish cooperative environments where individuals, regardless of their skill levels, can acquire knowledge and access the realm of digital manufacturing. In this context, the ultimate aim is to transform consumers into creators by harnessing shared expertise within the community, thereby promoting user empowerment and autonomy (E. Toscano, 2022). Therefore, Fab Labs represent places where relationships and collective dynamics, together with available technical instrumentation, foster the development of technological citizenship (Smith et al., in E. Toscano, 2022) to create alternative visions to industrial production models and inspire people to transform their ideas into objects.

1.2.2

A glimpse of Digital fabrication

The creation of an object, seen as a physical entity, is influenced by the production context in which it originates to a significant degree. Likewise, the designer's role within this context is closely intertwined with it. Craftsmanship and industrial production processes introduce distinct constraints involving feasibility, skills, time, cost, equipment, and materials. The intricate interplay among these factors not only shapes the tangible form of the object but also determines the degree to which it faithfully embodies the designer's original vision. According to Oxford University Press, *fabrication* commonly refers to the "process of creating or producing goods, equipment, etc. from various materials" (Oxford Learner's Dictionaries). While this definition aptly captures the essence of crafting an artifact, it remains fairly broad, leaving room for exploration of boundary shades of the practice. Within these nuances, it becomes possible to delineate the concept of fabrication along various dimensions. When considering aspects related to the tools and technologies of production, a clear distinction emerges when comparing *analog* and *digital* fabrication methods.

While traditional manufacturing relies heavily on tools and machinery with a significant human manual component, digital fabrication operates in a fundamentally distinct manner. Here, the integration of computer-aided design and fabrication serves the purpose of "reducing the capital and expertise required for producing a wide range of physical objects" (J. Cutcher-Gershenfeld et al., 2018, p.9). In the contemporary commercial landscape, *Computer Numerical Control* (CNC) machines play direct or indirect roles in every stage of production, encompassing both the creation of products and the crafting of the tools used for production (N. Gershenfeld, 2012). Digital fabrication builds upon the foundations of two preceding digital revolutions: computational and communicational advancements (J. Cutcher-Gershenfeld et al., 2018). This digital approach to fabrication, in contrast to analog manufacturing, has paved the way for the establishment of production networks that have accelerated continuous technological and scientific progress, resulting in a "democratization of new creative tools" (N. Gershenfeld, 2012, p.48). Consequently, digital fabrication technologies have permeated various contexts, including schools, libraries, museums, universities, community centers, and even domestic environments (J. Cutcher-Gershenfeld et al., 2018). Their accessibility to diverse user groups has led to applications in specialized areas such as art replication, museum exhibitions, and the restoration of cultural heritage (R. Scopigno et al., 2014). However, the term *digital fabrication* still frequently evokes misconceptions and is often narrowly associated solely with 3D printing technology. In popular discourse, digital fabrication encompasses processes utilizing computer-controlled tools, stemming from the development of numerically controlled milling machines, pioneered by the Massachusetts Institute of Technology (MIT) in 1952 (N. Gershenfeld, 2012). Digital fabrication technologies can be categorized into two main groups: subtractive processes and additive processes.

Subtractive processes involve replicating a digital model by carving or sculpting a solid material block using a numerically controlled milling tool. This approach offers significant advantages in terms of material versatility, as it accommodates almost any material, including wood, stone, and metal. However, it encounters various limitations related to geometric and kinematic constraints imposed by the milling machine. Controlling the milling cutter's tip is a complex task, and path creation can be both time-consuming and costly. The process must consider physical movement limitations, necessitating an experienced operator. The complexity of these machines varies based on the number of axes they can operate on, ranging from 2-axis to 6-axis or more CNC machines that offer greater degrees of freedom, enabling rotation around the entire object (R. Scopigno et al., 2014). Additive processes, often referred to as 3D printing, involve creating a replica of the digital object by sequentially adding material layer by layer along a predefined, computer-controlled path. This technology offers several advantages, including independence from the geometric complexity of the object, providing designers with total design freedom. Working with a digital representation allows for flexible workflow adjustments, permitting editing and transformations before obtaining a physical object, which is impossible with analog prototyping. Consequently, 3D printing enables the production of highly precise prototypes in a relatively short time (R. Scopigno et al., 2014). From a sustainability perspective, this technology allows for material optimization, generates minimal to no waste, and permits reuse if the material has not undergone irreversible chemical changes (J.A. Madrid et al., 2023). Nonetheless, there are some disadvantages associated with 3D printing technology. Depending on the geometries involved, support structures may be required to prevent the object from collapsing during the printing process. These constructions are either printed concurrently with the object or installed onsite during the procedure. When dealing with the printing of plastics, even though they are frequently composed of water-soluble materials, eliminating them can prove challenging for intricate geometries. Additionally, manual surface finishing is often necessary to eliminate the visible layers created during the printing process. There are constraints on material thicknesses and types, and depending on the technology and material used, curing processes may be required to make the object chemically stable and robust. Various additive processes can construct objects layer by layer. Among the most commonly used technologies is *Fusion Deposition Modeling* (FDM), where a thin plastic filament is heated until it melts, extruded, and deposited to form the desired shape. Comparable to this is *Liquid Deposition Modelling* (LDM), where a viscous fluid substance, typically clay, is extruded at a low temperature either through pressure or gravity casting. The Granular Materials Binding technique aggregates small particles layer by layer using agents such as gypsum powder, gelling agents, and resins. In *Selective Laser Sintering* (SLS), composite polymer powders or metals (*Selective Laser Melting*, SLM) are sintered using a laser tool. *Photopolymerization*, another popular method, involves gradually exposing printing resin to UV lights, causing it to polymerize and form the various layers of the artifact (R. Scopigno et al., 2014).

1.2.3

Alive materials

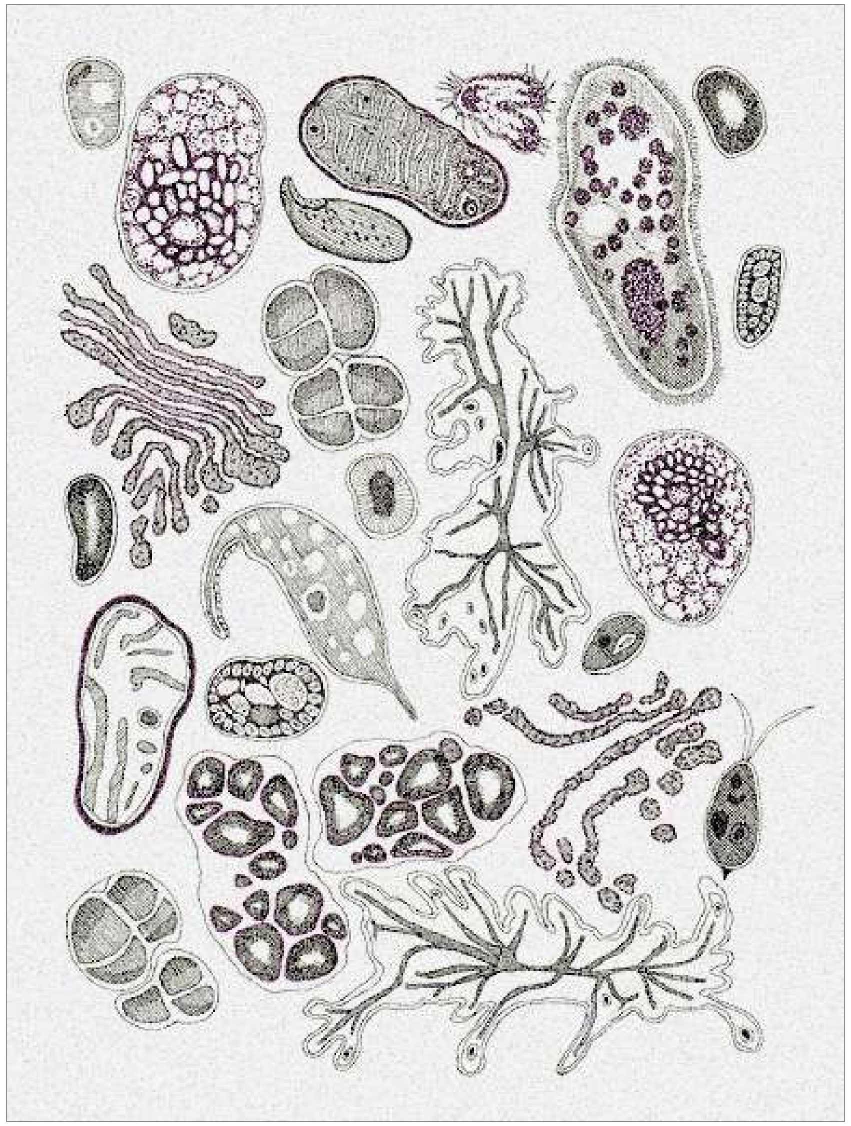
Materials hold immense potential to drive change, influencing both research and practical applications in the field of design, as well as shaping people's lifestyles and daily experiences (E. Karana et al., 2019). Nigel Cross (2008) argues that the approach of designers to product design must evolve beyond the current systemic methodology. Products should no longer merely represent the physical and material realization of ideas stemming from problem-solving exercises. Barati and his co-authors (in E. Karana et al., 2019) assign to the design profession the responsibility of actively engaging in the exploration of new material possibilities, departing from the conventional approach of translating known potentials into product applications. This call for innovation, both in materials development and the design approach towards them, opens up a broad spectrum of opportunities to create novel material experiences.

This shift ushers in a horizon where materials are no longer viewed as static or finite but rather dynamic and adaptive in both design and utilization (E. Karana et al., 2019). New perspectives emerge wherein materials used by humans can be cultivated from living organisms like fungi, algae, bacteria, and yeasts. For Petrera et al. (in E. Karana et al., 2019), materials are described as *alive*, *active*, and *adaptive*, expressing these attributes beyond biological and computational characteristics alone. The term *alive*, as defined by Hobye and Ranten (in E. Karana et al., 2019), conveys unique material expressions where computational materials adapt and come to life through interaction. Contemplating the living and dynamic nature of materials suggests that this evolving design approach has relevance not only for innovative smart materials or those rooted in the realm of biology but also for reimagining everyday, commonplace materials. Jenny Bergström et al. (2010) introduce the concept of *becoming materials* to highlight the inherent potential of materials and its implications for the field of design. They focus not only on what has already been explored but, more significantly, on the untapped possibilities residing within all materials. Their perspective emphasizes not only the latent potential from a scientific investigation standpoint but also how designers can harness this potential. They underscore the mutual relationship between designers and materials, where materials not only undergo shaping but also influence usage patterns and users' choices, highlighting their

Img.07
Material sample from Kombucha ARP by Adrien Rigobello, 2019. Kombucha bacterial cellulose (KBC) is a biomaterial consisting on a floating film produced by acetic acid bacteria during the fermentation of kombucha, in which tea and sugar are the main ingredients.

role as shapers of decisions. Similarly, Elvin Karana et al. (2019) define material potentiality as a principle stemming from the synergy of "situated actions, reflections, and collaborative actions of people, materials, production processes, and the surrounding environment" (E. Karana et al., 2019).

Materials can be perceived as boundless entities, constantly evolving and adaptable in response to context and utilization. Within this framework, designers assume the role of mediators and facilitators. This new perspective extends beyond materials alone and offers a platform for testing problem-solving models required to address the environmental crisis looming upon us in this century. Leonardo Caffo, in his book *Velocità di fuga* (E 2022), endeavors to decode the contemporary world using six words: Wait, Simplicity, Ecology, Isolation, Anticipation, Offlife. In his analysis, he introduces the concept of *Velocità di fuga* (escape velocity) as a means to transcend the gravitational pull of anthropocene logic, utilizing the six aforementioned words. Delving into the ecological crisis, he contemplates a new form of existence where the mantra shifts from *consume* to *use*. Caffo (2022) defines ecology as "a form of knowledge aimed at managing the protection of the real that has been given to us" (p.57), advocating a radical shift in perspective that widens our field of vision to include the viewpoints of animals, plants, stones, clouds, fungi, insects, and more. The discourse of using versus consuming as a novel philosophy of materiality initiates a discussion about the untapped potentials residing within the reality that surrounds us, echoing the idea of *becoming materials* mentioned earlier. By emphasizing these aspects, the author introduces the concept of ecology as a way of living, rejecting the notion of it as merely a *photograph of reality*. Instead, he elevates it to "a system of possible worlds toward which to orient the future," defining it as a "strange and impossible polaroid of the world to come" (p.46). The Anthropocene represents an ending era, where the idealized notion of progress has pushed us to the brink, prompting a reconsideration of the true meaning of this word. We are entering what Caffo terms as the *Età della velocità di fuga* (Age of Escape Velocity). The choice between escape as denial of system collapse and escape as detachment from the myth of progress through embracing ecology as a way of life becomes an unavoidable decision. In the face of the Anthropocene's decline, "escape is consummated either positively or negatively, and the only thing that will not be possible is stasis" (p.45). The theoretical insights previously discussed regarding *alive materials* and the concept of *using without consuming* find practical application in the field of BioDesign. As described by W. Myers (in S. Chambers et al., 2017, p.102), BioDesign represents an emerging and often radical approach to design rooted in biological principles and incorporating the use of living materials in structures, objects, and tools. When delving into biology and *dynamic materials*, the designer's role necessarily interfaces with the concept of nature. While nature remains central to this relationship, what changes is the designer's position in relation to it, leading to various approaches. Carole Collet (in S. Camere et al., 2017, p.102) identifies five categories that characterize the relationship between design and nature: (1) Nature as a model, (2) Nature as a co-worker in the design process, (3) Nature as reprogrammed and synthetic, (4) Nature as hybridized with non-living technologies, and (5) Nature as conceptualized and envisioned in a provocative distant future.



^ Img.08
Mitochondria, an illustration by Terry Rosen.

Img.09
Material sample from Algae Lab, a bio-laboratory that researches the potential of growing micro- and macro-algae and discovering their uses. Algae Lab is a project from Studio Klarenbeek & Dros initiated with Atelier Luma in 2017.

1.2.4
Embracing a Biofabricated Future

Nature as co-worker in design process, the second category, as identified by Carole Collet, holds particular significance in light of the arguments presented thus far. Under this approach, the product is the outcome of a collaborative process between humans and living organisms, characterized by a reciprocal relationship. Here, the designer's actions and choices are influenced by the material's responses, while simultaneously, human actions influence the natural growth of the material. This perspective is also explored by Serena Camere et al. (2017) in their examination of four primary material design practices intersecting biology and design. Before delving into the other categories and establishing connections between them, let's first explore the essence of *Augmented Biology* and *Bio Design Fiction*.

Augmented Biology is a field where design intersects with synthetic biology, enabling the manipulation of living organisms through engineering principles. Its objective is to reimagine the natural world, by hacking it and striving for rapid, consistent, and predictable outcomes. In contrast, Bio Design Fiction represents a design approach focused on exploring potential futures, often from a critical and thought-provoking standpoint. This is achieved by crafting speculative scenarios that involve design's interaction with living and natural ecosystems.

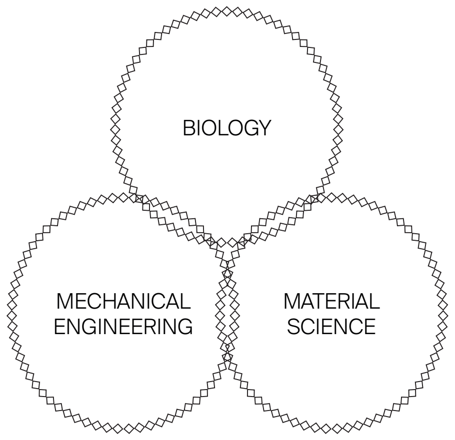
Next, we turn to *Growing Design*, which encompasses an approach to materials stemming from advancements in biotechnology research. It involves the use of materials cultivated from living organisms, such as fungi, algae, bacteria, and yeasts (S. Camere et al., 2017). This practice is deeply rooted in artisanal methods, to the extent that the direct interaction between the designer and the material can be likened to a DIY practice (Rognoli et al., in S. Camere et al., 2017, p.101). Materials are nurtured by designers through organic manufacturing processes, guided and controlled to achieve desired outcomes. Designers adopt production strategies inspired by nature, without altering the genetic composition of the materials or attempting to redesign nature itself.

The primary advantage of Growing Design lies in its sustainability aspect: materials are *grown* following natural processes, as opposed to being manufactured using highly polluting industrial methods.

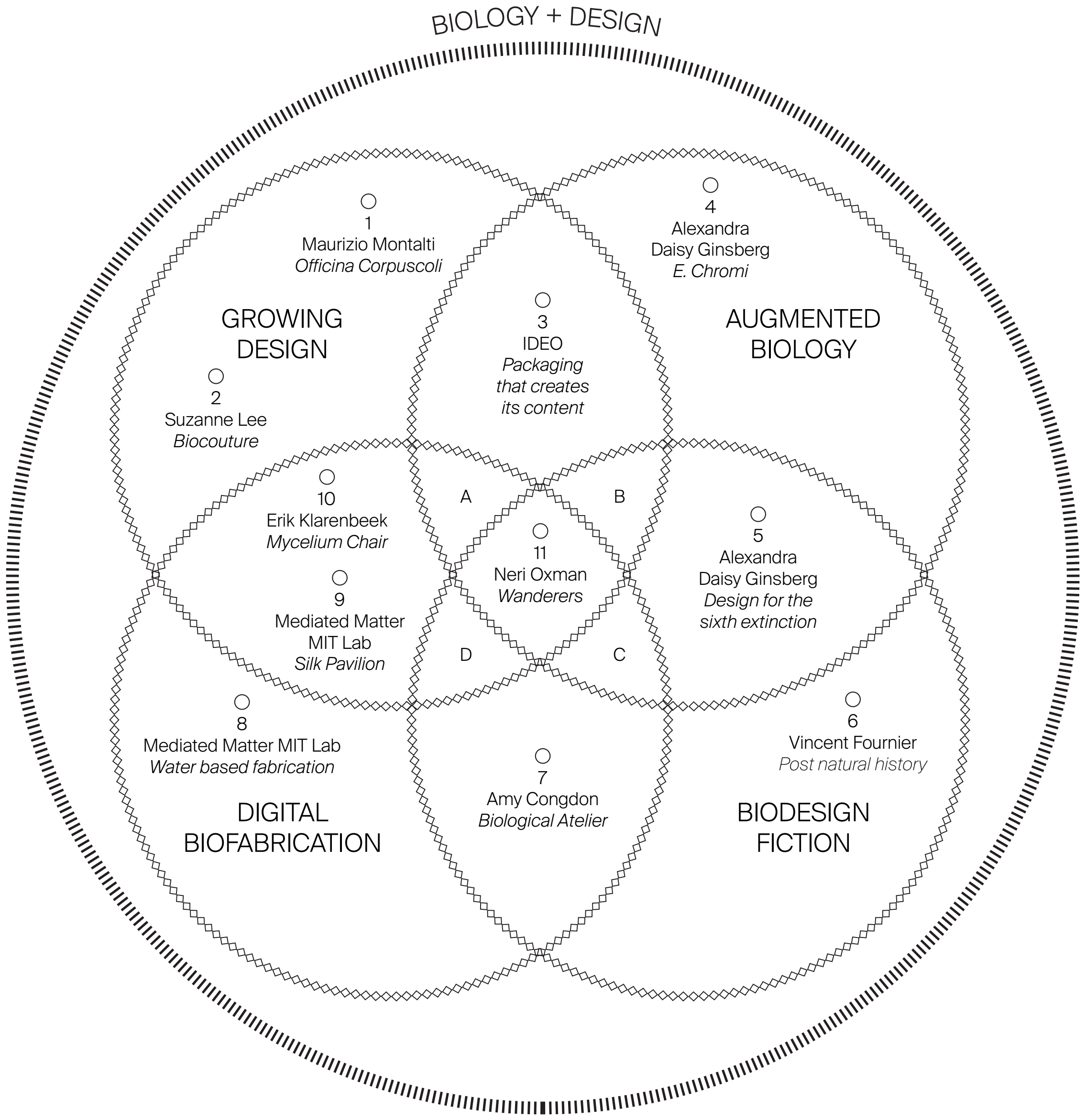
Additionally, designers have direct control over the means of production, enabling highly customized and adaptable products and processes. However, this approach presents challenges related to precise material growth control and scalability. Artisanal processes, by definition, are challenging to scale, posing a significant barrier to the widespread adoption of Growing Design practices. These complications affect the ability of these innovate materials to compete with traditional materials, which have established and refined industrial production methods.

Digital Biofabrication, in contrast, emerges from the fusion of three distinct disciplines that form its foundation: biology, mechanical engineering (comprising CAD and additive manufacturing), and materials science (specifically biomaterials) (V. Mironov et al., 2009). To provide a definition, Digital Biofabrication can be characterized as “the creation of intricate biological entities using living cells, molecules, extracellular matrices, and engineered biomaterials” (V. Mironov et al., 2009, p.2) involving the “hacking of Nature through Digital Fabrication [...] performed by designers who realize a digitally-inspired Nature” (S. Camere et al., 2017, p.103). The primary distinction between Digital Biofabrication and Growing Design lies in the intersection of engineering and biology. The former finds applications in more technical and specialized contexts, such as the medical field, thanks to the exceptional precision and capabilities offered by digital fabrication tools. In the realm of Digital Biofabrication, intricate biological products like artificial tissues and organs are constructed by depositing cells or organisms layer by layer with remarkable precision. Serena Camere et al. (2017) highlight how digital biofabrication technology encompasses a range of tools, including mathematical modeling, additive manufacturing, and digital models of material behavior. Consequently, this practice holds a dual significance: it serves not only as a means of production but also as a behavioral model for living organisms (p.103). Unlike Growing Design, where the designer plays a guiding but limited role in controlling material growth during the growth phase, Digital Biofabrication involves both the machine and the human collaboratively assuming this role. Digital tools serve as potent instruments for anticipating and precisely designing material growth behavior. As a result, the products manifest as outcomes of a “symbiotic relationship in which biologically and digitally designed materials mutually contribute to structural stability” (J. Zhou et al., 2021, p.112). Both Growing Design and Digital Biofabrication achieve a reduction in energy consumption for material generation by harnessing the metabolic rates of the biological systems they employ. This reduction leads directly to a diminished ecological footprint and the develop-

Img.10
Pillar disciplines at the basis of the rise of Digital Biofabrication practice. Graphic redesign of the scheme in V. Mironov et al., 2009.



Img.11
Four approaches to Bio-design with related case studies: 1) materials and products from mycelium; 2) a collection of clothing from bacterial cellulose; 3) packaging grown from engineered bacteria too produce its content; 4) self-diagnosis toolkit using engineered Escherichia coli; 5) Designed organisms to revive ecosystems in a speculative future; 6) luxury fashion items for 2080 grown from biocells; 7) Speculative encyclopedia of new living species; 8) biomaterials manufactured using additives production; 9) digitally fabricated structure completed by silkworms; 10) Completed 3D printed chair from mycelium; 11) Bioaugmented wearable garments for extreme planetary environments.
Graphic redesign of the scheme in Camere & Karana, 2017.



ment of entirely biodegradable textiles and materials. At the conclusion of their life cycle, these materials can serve as nutrients for the production of fresh bio-based materials (Jones et al., 2017 & Jiang et al., 2013). In this context, the role of the designer takes on a pivotal significance, serving as a mediator and facilitator throughout the entire process. The designer collaborates with both nature and machines to achieve specific design objectives, resulting in the creation of intricate products comprised of living tissue. This entails the responsibility of devising and developing a system that harmonizes digital tools with biological structures, ensuring that the design optimally aligns with functionality and meets the necessary biological criteria. The complementarity between human action and the workings of nature, supported by advanced fabrication methods, gives this practice extraordinary potential that is still largely unexplored. Designers of today and the future must therefore adopt a perspective that addresses materials as intelligent agents capable of adaptive responses to their surrounding environment, an environment they actively contribute to shaping and where the dialogue between nature and designer takes place.

The immense potential of Digital Biofabrication necessitates a transition toward a new manufacturing approach. This approach should minimize energy and resource requirements, exhibit flexibility in responding to local demand, harness local resources, and intercept industrial waste streams to achieve zero waste impact. Suzanne Lee (TEDx Talks, 2019) emphasizes that "we have no choice but to biofabricate our future." In a sustainable future, consumer materials should no longer originate from plants or animals; instead, they should be derived from living organisms. This entails a reimagining of new factories as living cells in alignment with the principles of the *Fourth Industrial Revolution*, a phase characterized by the digitalization of production that blurs the boundaries between the physical, digital, and biological realms (C. Sàinz de la Flor, 2020). Organisms such as algae, fungi, bacteria and yeasts become "design tools that can replace multiple man-made steps with a single step performed biologically." Suzanne Lee states that "as we begin to grow materials with living organisms, this begins to make previous production methods seem illogical" and that ideally "the designed material world should not compromise our health or that of our planet." In this regard, back in 2015 Neri Oxman (TEDx Talks, 2015) spoke of *material ecology* to describe the need to "move from the machine age to a new era of symbiosis between our bodies, the microorganisms we inhabit, our products, and even our buildings." For her, the concept of *evolution* must be seen in terms of design and not natural selection, with a whole new potential whereby "two organisms that have never met each other are engineered for the first time to build a relationship with each other." For Oxman (TEDx Talks, 2015), the achievement of this *material ecology* represents the final frontier of design in which designers of the future will be able to combine two opposing worldviews and design cultures, "one synthetic and one organic, one assembling and one growing." It ushers in a "new era of design [...] that takes us from nature-inspired design to design-inspired nature, and asks us for the first time to be the mother of nature." This thesis work will focus specifically on the latter topics mentioned, conducting a combined theoretical and on-field investigation of the potential of a traditional material such as clay which, in accordance with the concept of becoming materials expressed above, will be analyzed from a different perspective proper to the designer. Specifically, the challenges and opportunities generated by the intersection between this material and a living organism such as *mycelium* will then be analyzed, entering fully into the practical field of Digital Biofabrication.

Alonso Madrid, J., Sotorrío Ortega, G., Gorostiza Carabaño, J., Olsson, N. O., & Tenorio Ríos, J. A. (2023). 3D Claying: 3D Printing and Recycling Clay. *Crystals*, 13(3), 375.

Bergström, J., Clark, B., Frigo, A., Mazé, R., Redström, J., & Vallgårda, A. (2010). Becoming materials: material forms and forms of practice. *Digital Creativity*, 21(3), 155-172.

Caffo, L. (2022). Velocità di fuga (1a ed.). Torino: Giulio Einaudi editore.

Camere, S., & Karana, E. (2017, June). Growing materials for product design. *In Alive. Active. Adaptive: proceedings of international conference on experiential knowledge and emerging materials (EKSIG 2017)* (pp. 101-115).

Carrington, D. (2016). The Anthropocene epoch: scientists declare dawn of human-influenced age. *The Guardian*, 29(08), 2016. Available at: https://www.theguardian.com/environment/2016/aug/29/declare-anthropocene-epoch-experts-urge-geological-congress-human-impact-earth (Accessed: 15 March 2023).

Carrington, D. (2017). Earth's sixth mass extinction event under way, scientists warn. *The Guardian*, 10, 2017. Available at: https://www.theguardian.com/environment/2017/jul/10/earths-sixth-mass-extinction-event-already-underway-scientists-warn (Accessed: 15 March 2023).

Casselman, A. (2007). Strange but true: the largest organism on earth is a fungus. *Scientific American, 4*. Available at: https://www.scientificamerican.com/article/strange-but-true-largest-organism-is-fungus/ (Accessed: 27 March 2023).

Cutcher-Gershenfeld, J., Gershenfeld, A., & Gershenfeld, N. (2018). Digital fabrication and the future of work. *Members-only Library*, 22.

Frascara, J. (2007). Hiding lack of knowledge: Bad words in design education. *Design issues*, 23(4), 62-68.

Fremstad, A., & Paul, M. (2022). Neoliberalism and climate change: How the free-market myth has prevented climate action. *Ecological Economics*, 197, 107353.

Gershenfeld, N. (2012). How to make almost anything: The digital fabrication revolution. *Foreign Aff.*, 91, 43.

Greenwood, M., (2021). How Neoliberalism Destroyed the Planet and Why Capitalism Won't Save Us. *The University of Manchester*, 4 May [Online]. Available at: https://sites.manchester.ac.uk/global-social-challenges/2021/05/04/how-neoliberalism-destroyed-the-planet-and-why-capitalism-wont-save-us/ (Accessed: 21 April 2023).

Hansson, K., Forlano, L., Choi, J. H. J., DiSalvo, C., Pargman, T. C., Bardzell, S., ... & Joshi, S. (2018). Provocation, conflict, and appropriation: The role of the designer in making publics. *Design Issues*, 34(4), 3-7.

Howkins, J. (2020). Invisible Work: The Hidden Ingredient of True Creativity, Purpose and Power, 1ed. *Tewksbury: September Publishing*.

Jiwei Zhou, Bahareh Barati, Jun Wu, Diana Scherer and Elvin Karana (2021) 'Digital biofabrication to realize the potentials of plant roots for product design', Bio-Design and Manufacturing, 4(1), 111-121.

Julier, G., & Kimbell, L. (2019). Keeping the system going: Social design and the reproduction of inequalities in neoliberal times. *Design Issues*, 35(4), 12-22.

Karana, E., Nimkulrat, N., Giaccardi, E., Niedderer, K., & Fan, J. N. (2019). Alive. Active. Adaptive: Experiential knowledge and emerging materials. *International Journal of Design*, 13(2), 1-5.

Kuznetsov, S., & Paulos, E. (2010, October). Rise of the expert amateur: DIY projects, communities, and cultures. *In Proceedings of the 6th Nordic conference on human-computer interaction: extending boundaries* (pp. 295-304).

V. Mironov, T. Trusk, V. Kasyanov, S. Little, R. Swaja, R. Markwald (2009), ' Biofabrication: a 21st century manufacturing paradigm', Biofabrication, 1(2), 1-16.

Monbiot, G. (2016). Neoliberalism–the ideology at the root of all our problems. *The guardian*, 15 April. Available at: https://www.theguardian.com/books/2016/apr/15/neoliberalism-ideology-problem-george-monbiot (Accessed: 16 March 2023).

Morelli, N. (2007). Social Innovation and New Industrial Contexts: Can Designers "Industrialize" Socially Responsible Solutions?. *Design issues*, 23(4), 3-21.

Oxford Learner's Dicitionaries [Online]. Available at: https://www.oxfordlearnersdictionaries.com/definition/english/fabrication?q=fabrication (Accessed: 28 February 2023).

Papanek V. (2019). Design for the Real World, 3ed. London: Thames & Hudson Ltd.

Sáinz de la Flor, C. (2020). Manuale per comprendere la Quarta Rivoluzione Industriale, *We Are Marketing*, 22 October [Online]. Available at: https://www.wearemarketing.com/it/blog/cos-e-la-quarta-rivoluzione-industriale.html (Accessed: 30 March 2023).

Scopigno, R., Cignoni, P., Pietroni, N., Callieri, M., & Dellepiane, M. (2014). Digital Fabrication Technologies for Cultural Heritage (STAR), GCH 2014 - *Eurographics Workshop on Graphics and Cultural Heritage* [Online]. Available at: http://diglib.eg.org/handle/10.2312/gch.20141306.075-085

Sloane, M. (2019). On the need for mapping design inequalities. *Design Issues*, 35(4), 3-11.

Staff Reporter (2011) 'People are the real wealth of nations', Mail & Guardian, 22 Marzo [Online]. Available at: https://mg.co.za/article/2011-03-22-people-are-the-real-wealth-of-nations/ (Accessed: 14 April 2023).

TEDx Talks [TEDxTalks]. (2015). Design at the Intersection of Technology and Biology| Neri Oxman | Available at: https://www.youtube.com/watch?v=CVa_IZVzUoc (Accessed: 28 March 2023).

TEDx Talks [TEDxTalks]. (2019). Why "biofabrication" is the next industrial revolution | Suzanne Lee | Available at: https://www.youtube.com/watch?v=7pMhqyteR5g (Accessed: 28 March 2023).

Toscano, E. (2022). Fablab, movimento maker e DIY culture. Uno studio di caso sugli spazi di fabbricazione digitale nel Lazio. *Digicult Scientific Journal on Digital Cultures*, 8(1), 11-23.

Willis, A. M. (2006). Ontological designing. *Design philosophy papers*, 4(2), 69-92.

Zincone, V. (2011) 'Enzo Mari', *Sette*, 14 Aprile [Online]. Available at: http://vittoriozincone.it/2011/04/14/enzo-mari-sette-aprile-2011/ (Accessed: 14 April 2023).

CHAPTER 2

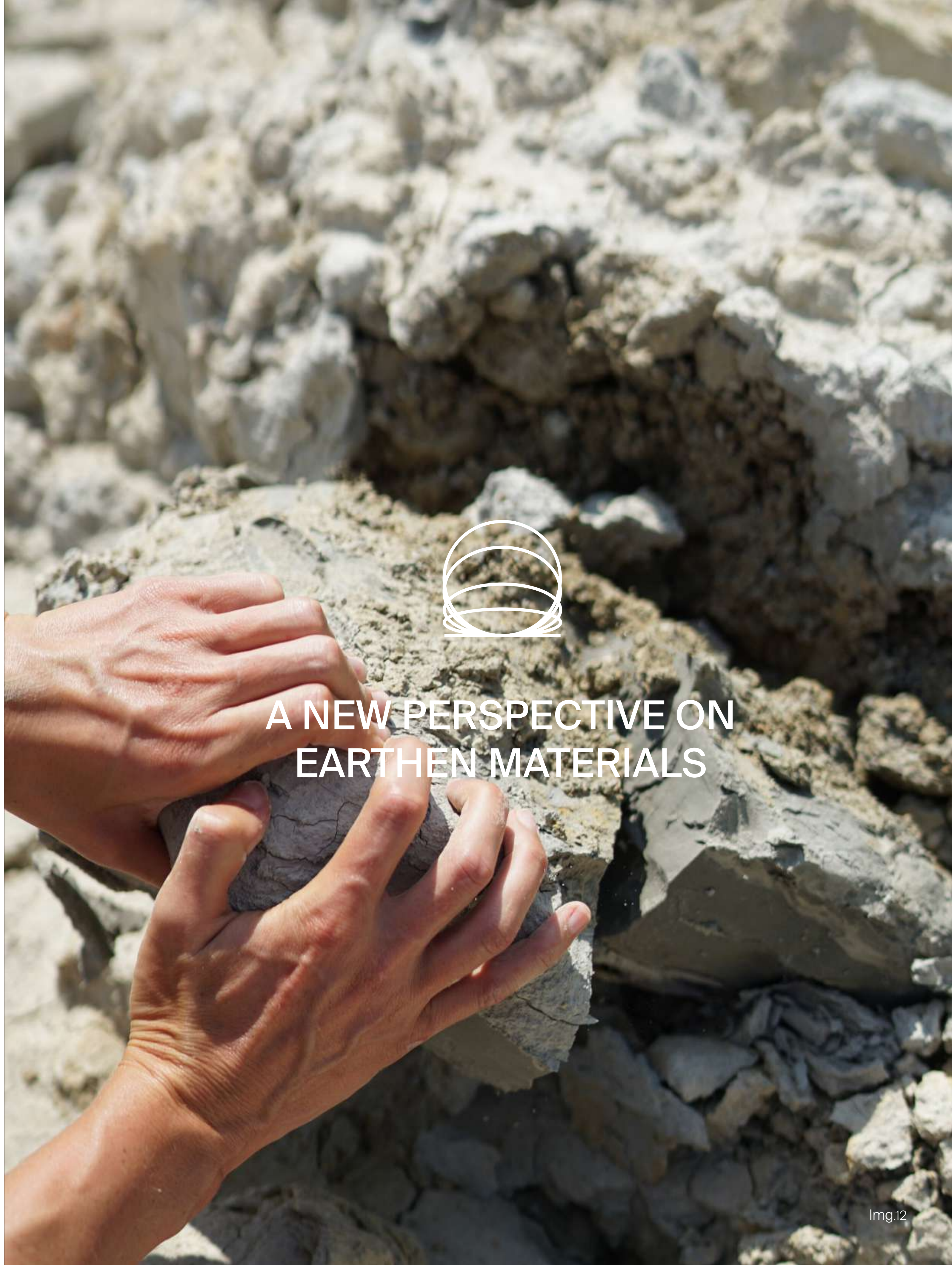
2.1 FROM CLAY TO CERAMIC

2.2 IS CERAMIC REALLY AN ECO-MATERIAL?

2.3 UNFIRED CLAY AND UBWCCs

2.4 CLAY 3D PRINTING

… While ceramics do possess ecological qualities, advocating for their unrestricted use within the context of current industrial practices may appear misleading at best. Indeed, while pottery originates from clay and other raw materials abundantly found in nature, it's important to recognize that the Earth takes centuries, if not thousands of years, to regenerate these raw clay deposits. These materials, aggregates composed of fine particles resulting from natural erosion over millennia, technically represent a naturally regenerating material. However, it must be acknowledged that human extraction and consumption of clay far outpace the Earth's regenerative rhythms …



A NEW PERSPECTIVE ON EARTHEN MATERIALS

Img.12

FROM CLAY TO CERAMIC

2.1

2.1.1

Raising from the Earth's core

As per the U.S. Geological Survey (USGS), the term *clay* is employed to describe sedimentary materials composed of soil particles whose size measures less than 2 micrometers, equivalent to one-millionth of a meter. Beyond this sediment category, *clay minerals*, which are rocks possessing distinctive chemical and structural characteristics typical of phyllosilicates, also fall into this classification. These minerals exhibit well-defined crystalline structures consisting of interconnected tetrahedral chains linked by oxygen bridges. Chemically, clay minerals predominantly comprise elements such as silica, alumina, magnesia, iron, potassium, sodium, and calcium (Encyclopedia Britannica, 2023). In a taxonomical context, the term *clay* thus encompasses both materials with particle sizes below 2 micrometers and a family of variably grained minerals that share similar chemical compositions and common crystalline structural features. Clays and clay minerals are primarily found at or near the Earth's surface, although a wide array of rocks, distributed across virtually every corner of the planet, meet this definition. This category encompasses soils, ceramic clays, clay shales, mudstones, glacial clays (including substantial volumes of detrital and transported clays), and deep-seated clays like red clay, blue clay, and blue mud. The formation of most clays results from prolonged exposure to atmospheric and geological processes, including the accumulation of continental and marine sediments, the influence of geothermal activity, and the deposition of volcanic material layers (Encyclopedia Britannica, 2023).

At the property level, clay materials exhibit common behavioral traits due to their chemical composition, layered structure, and particle size. Generally, they all display a strong affinity for water, meaning they interact with water molecules that are attracted to their surfaces. When clay absorbs water, it undergoes a volume expansion, the extent of which can be reversed depending on environmental factors, primarily moisture and temperature. The degree of hydration has a direct impact on the physical size of the constituent particles by altering the arrangement of the bonds forming the three-dimensional lattice responsible for clay's plasticity. Upon contact between clay and water, the water particles disperse evenly within the material, allowing for the adjustment of lattice plasticity in response to the amount of liquid present. Mixing clay with a small amount of water results in a muddy blend with plastic behavior, capable of being shaped and retaining its form after drying, ultimately forming a relatively rigid solid. Due to their exceptional water-absorbing capacity, clays are referred to as pseudocoherent rocks. This term signifies that their mechanical properties are not determined by particle friction but rather by cohesion, which is directly linked to the material's hydration state (Encyclopedia Britannica, 2023).

In contrast to typical soils, clay materials stand out for their malleability and capacity to maintain their shape without fracturing. This pliability arises from the interactions between three-dimensional lattice bonds and water molecules at the microscopic level. When clay and water meet, their particles disperse and align, allowing water molecules to act as lubricants, enabling the clay particles to slide over one another during processing. Another key factor contributing to the moldability of clay in humid conditions is the morphology of its constituent particles. These particles take the form of flat, hexagonal plates with an elongated, slender shape. This unique shape enables the creation of a matrix during the working of the clay, with particles aligning in a shared direction, providing strength and cohesiveness. The crystal lattice structure of clay dictates its distinctive properties during shaping, shrinkage, and expansion in relation to its hydration state and affinity for water. A thorough understanding of the chemical structure of clay particles is essential for comprehending and predicting its behavior throughout the shaping, drying, and firing processes it undergoes (L. Anne, 2022). The moldable nature of clays and pseudocoherent rocks has been harnessed by humanity since the Stone Age for crafting a diverse array of useful artifacts. Reflect on the pivotal role clay has played throughout history, contributing to the advancement of civilizations through the creation of agricultural tools, culinary vessels, and the preservation of archaeological treasures that provide insights into the artistic achievements of ancient societies like the Romans, Greeks, and Chinese. The whole history of humankind is intimately intertwined with this material, as much of our progress is rooted in its discovery and utilization. Even in contemporary times, the extraction of these materials and their transformation into various objects remains a fundamental practice across a wide spectrum of manufacturing industries. This enduring relevance stems from clay's exceptional properties, including porosity, aeration, water retention, filtration capabilities, thermal insulation, and structural stability. No other substance rivals its versatility and importance, as it continues to find applications in diverse fields, spanning from the creation of everyday items to environmental, cosmetics, construction, engineering solutions, and even modern innovations within the medical sector.

2.1.2

Eight stages of clay

The mentioned application practices often demand exceptionally high material performance. These demands underscore the necessity of subjecting the material to a stabilization process, which alters its chemical and physical properties prior to use. Among these characteristics, the primary objective is to enhance the durability and water resistance of the artifacts. This stabilization process involves the crucial step of *firing* the clay, turning it into a distinct material known as ceramics. This transformation unfolds within kilns capable of achieving exceedingly high temperatures, instigating reactions that bring about a profound alteration in clay's properties. During the firing phase, clay undergoes chemical changes, and the outcomes, both in terms of aesthetics and properties, can be tailored based on the specific technologies and methodologies applied in the process. The subsequent paragraphs will delve into the methods and principles governing the firing process, elucidating how clay is chemically transformed into ceramics. However, before delving into this topic, it is imperative to establish an understanding of the initial stages of crafting a clay object and the preparatory steps it must undergo before entering the firing process that ultimately results in its metamorphosis into ceramics.

In this context, it becomes necessary to introduce the eight stages of clay processing that culminate in its transformation into ceramics. These stages involve a comprehensive analysis of the chemical and physical changes that transpire from one phase to the next. Particularly, we observe how these alterations are intimately tied to the clay's hydration state, shedding light on the opportunities, constraints, and challenges associated with working with such a semi-coherent material. In summary, the processes of working with clay are segmented into the following eight stages: (1) Raw Clay, (2) Dry/powdered clay, (3) Slip clay, (4) Workable clay, (5) Leather hard clay, (6) Bone dry clay, (7) Bisqueware, (8) Glazeware. Lesley Anne (2022) provides a detailed outline of each of the various steps just mentioned, which is summarized below.

(1) This initial stage entails the clay in its natural state, often referred to as *wild*. It is extracted directly from the Earth, frequently through manual labor or industrial methods involving excavation or clay mining. The extracted clay is typically found in the form of wet clumps containing stones, organic matter, and various impurities. These clumps are transported to processing facilities where they undergo chemical analysis to determine their mineral content. This analysis allows for the categorization of clay into different types suitable for specific purposes. The clumps are subsequently broken down and dried using kilns. Once in a dry state, the mixture can be pulverized, and impurities removed, resulting in pure powdered clay. This purified material can be further processed and marketed either as a powder or as a blend that can be molded by adding an appropriate amount of water.

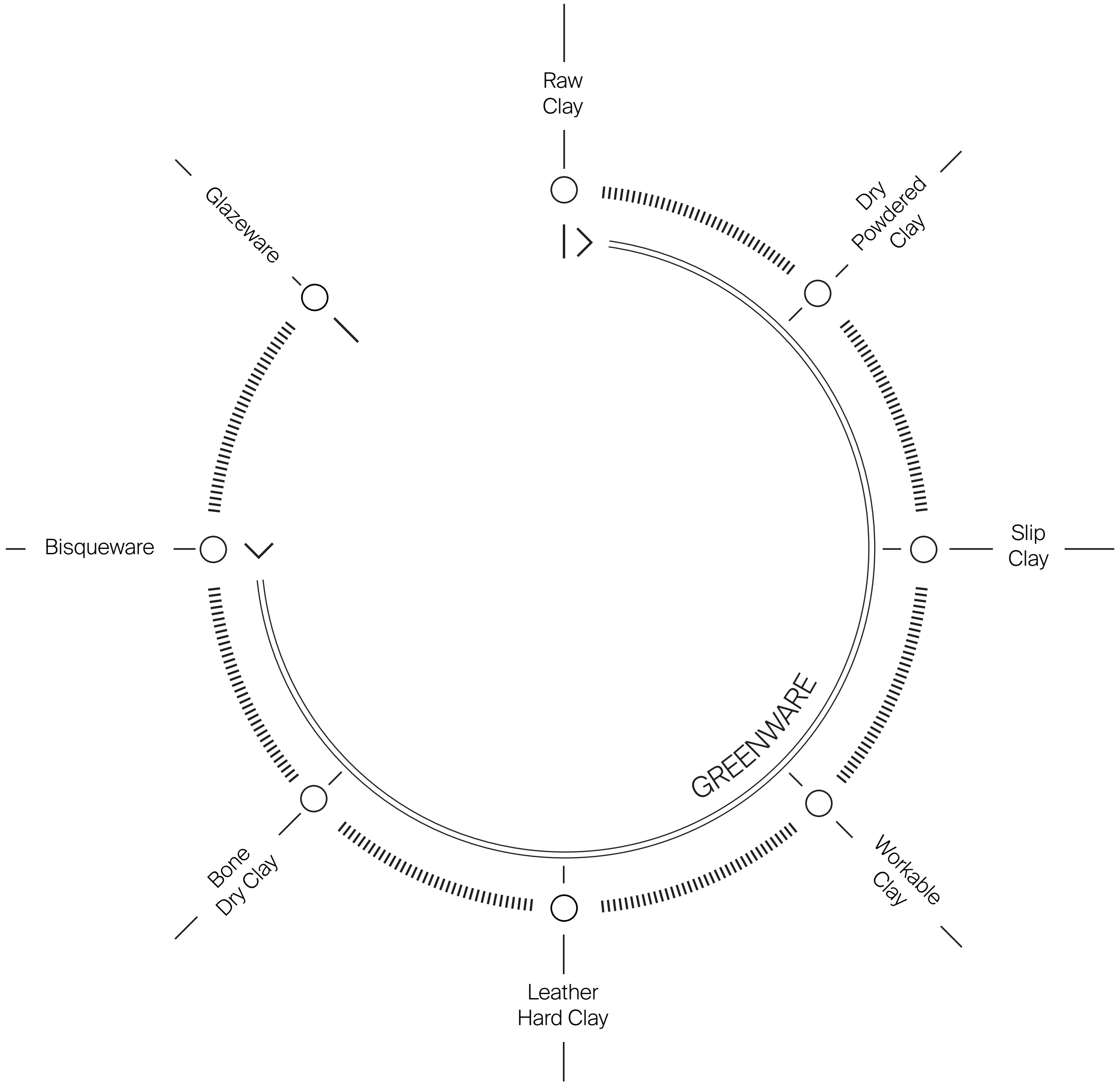
Img.13, 14
Hand-harvesting of the wild material from the claylish soil, Unurgent argilla material archive, Nina Salsotto Cassina.

(2) Pure clay is made commercially available either in the form of hydrated slurry or as dry powdered clay. The hydrated slurry consists of powdered clay to which water has already been added. This material constantly interacts with its environment, exchanging moisture with the surrounding air. When crafting objects from clay, it becomes evident that they tend to dry out relatively quickly upon exposure to air. This can affect the material's plasticity, sometimes necessitating the addition of more water to restore its moldable consistency. At this stage, the material remains entirely reusable, meaning that even as it undergoes changes in consistency due to dehydration, dried-out remnants can still be reconstituted. To achieve specific qualities in the mixture, different clay types or additional materials can be blended using various recipes. It's crucial to keep in mind that different elements may absorb varying amounts of water.

(3) If excessive water is added to the mixture, it results in a highly liquid, muddy substance known as slip clay. This comprises a solution of dissolved clay particles suspended in water. Slip clay serves various purposes, including acting as an adhesive for joining

EIGHT STAGES OF CLAY MANUFACTURING PROCESS

Img.15
Grapich representation of the clay to ceramic manufacturing process divided into the main eight stages. Each of them involves chemical and physical changes that transpire from one phase to the next. Particularly, we observe how these alterations are intimately tied to the clay's hydration state. Content data from Lesley Anne 2022.



two clay pieces through welding, creating decorative details, or facilitating the casting of artifacts using molds. Generally, it is possible to control the viscosity of the mixture by adjusting the water content in the clay powder or by adding powdered material to the slip. Ensuring a homogeneous mixture and preventing the formation of lumps is essential.

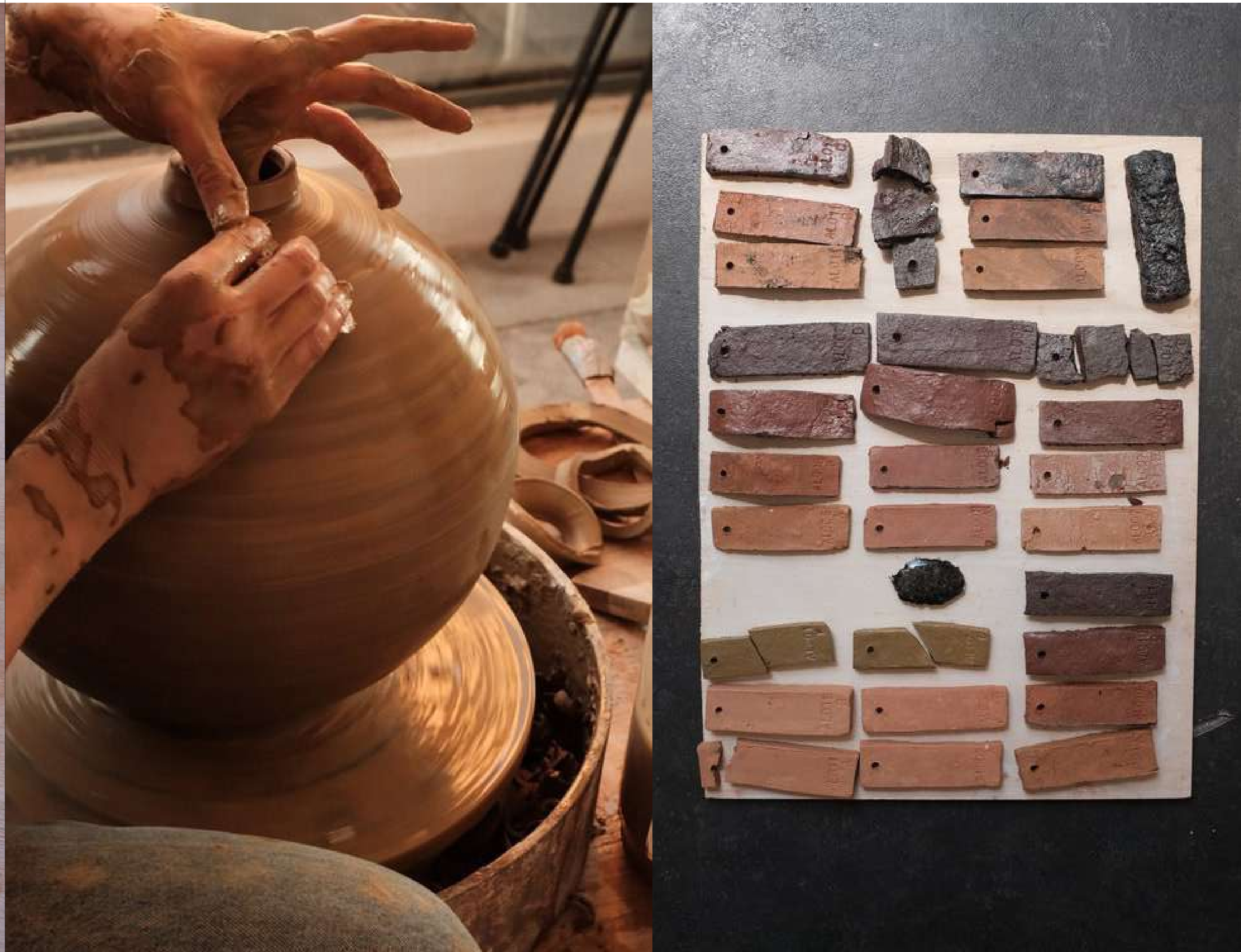
(4) Wet clay in this stage possesses a soft and malleable quality, exhibiting plasticity and ductility. This allows for shaping and maintaining the material's form, enabling bending without breakage.

(5) Following the processing stages, the piece enters a drying phase during which it gradually releases moisture to the atmosphere without undergoing rehydration. The clay loses a significant amount of moisture, causing the particles at a chemical level to cease sliding over each other when subjected to pressure, resulting in increased rigidity. This phase marks the loss of plasticity and workability, and the clay's consistency is termed *Leather hard clay*. Within this stage, there are subphases where the material remains malleable enough for superficial work without the risk of cracking. It is typically at this point that pieces are welded together using slip. Greater dehydration leads to increased material stiffness, making it suitable for carving and decorating. As the clay continues to exchange moisture with the air, it dries further, changing color and developing a powdery surface. At this stage, working the clay becomes impossible, and carving become less precise and riskier due to increased fragility and the potential for cracks to develop.

(6) When the clay has entirely shed all moisture before the firing process, it is referred to as *bone dry*. This material is significantly paler than its hydrated counterpart and is stiff and extremely brittle. Decorative elements such as handles or protrusions are particularly susceptible to breakage if not handled with care. The only operation possible at this stage, before firing the object, is surface finishing through sanding to remove minor defects or round off edges.

(7) The preceding six phases classify the clay as *greenware* or *green clay*, meaning it has not yet undergone irreversible chemical changes as it has not been fired in a kiln to transform it into ceramics. Greenware stands out for its solubility upon contact with water, remaining a semi-coherent material. To enhance its durability and insolubility, the next step is firing. This process occurs inside specialized ceramic kilns capable of reaching extremely high temperatures. Different kiln types and firing techniques exist, with electric kilns being the most common, followed by gas kilns and wood-fired kilns. Temperatures may range from 800 to 1700°C, depending on the type of clay used and the desired aesthetic outcome. In all cases, these temperatures must be sufficiently high to induce the chemical transformation of clay into ceramic material. The firing process of greenware is termed *bisque fire*, resulting in *bisqueware*, a product that is no longer water-soluble.

(8) While bisqueware is much stronger and less brittle than the bone dry state, it retains a porous surface capable of absorbing liquids. To render ceramics waterproof, they must undergo a glazing process, referred to as *glazing*. Glazing entails applying a vitreous coating to the object, providing both a waterproof surface and the opportunity for decorative enhancements using a variety of colors and glazing techniques. However, the ceramic glazing process necessitates an additional firing step. This is essential because glazes, in their liquid state during application, would compromise the integrity of greenware artifacts as they remain water-soluble. Glaze typically consists of silica, alumina, and flux blended into an aqueous solution, similar to paint, and is applied to surfaces using various methods. Once applied, the glaze dries to form a powdery coating that melts during the firing process and solidifies into a glassy substance during cooling. It's crucial to leave the bottom of the pieces unglazed, as a fully glazed piece would adhere to the kiln shelf during firing, resulting in the entire piece becoming stuck inside of it.



Img.16, 17, 18, 19
On the left page raw clay extraction and wet clays, on the right page handmaking of a clay vase on a potter's wheel and different bisqueware material samples, Unurgent argilla material archive, Nina Salsotto Cassina.

Img.20, 21
Various types of kilns are employed for firing clay, ranging from advanced solutions that allow precise digital control to DIY alternatives, such as brick kilns or pit furnaces dug into the ground. The images above show two different kind of ceramic klins, namely raku and electric klin. A Raku Kiln is generally a small kiln, which is used to get your pots up to temperature as quickly as possible, and is easy to open to get your pots out quickly. Raku is a Japanese style of pottery characterised by the removal of a clay object from the kiln at the height of the firing and causing it to cool very rapidly creating unique finishing. Electric kilns are the most commonly used by ceramicists. They are known for their ease of use and regulation through digital control panels. These kilns feature firing chambers lined with highly insulating and porous bricks. Embedded within the walls are metal coils through which high electric currents pass, serving as heating elements.

IS CERAMIC REALLY AN ECO MATERIAL?

2.2

2.2.1

Firing processes and methods

The preceding paragraphs elucidate the intricate process by which clay is transformed into ceramics through a series of intermediate steps that demand considerable time and equipment. Within these stages, the raw material undergoes gradual chemical alterations, transitioning from a semi-cohesive, pliable, and water-soluble substance into a rigid, porous material that is impervious to water. Essentially, the firing of ceramics serves the purpose of fortifying objects, rendering them durable and long-lasting, as they possess limited utility in their initial greenware state. This firing process is synonymous with the material's *maturation*, achieving the utmost levels of hardness and density attainable for the specific clay type employed (L. Anne, 2022). Understanding these processes is fundamental for potters to exercise control over the desired outcomes. Key factors include the clay type used, recipe mixture, appropriate drying duration, kiln type, and firing temperature, all of which play pivotal roles in crafting flawless and well-crafted ceramic artifacts. Notably, the choice of clay type impacts the achievable levels of hardness and density. There are five primary clay types employed in pottery: earthenware, stoneware, porcelain, ball clay, and fire clay. In sequential order, the first three types exhibit increasing maturity temperatures and correspond to earthy, glossy, and pale-white aesthetics, respectively. Ball clay and fire clay, conversely, are exclusively marketed in powder form and serve as additives alongside other clay types to enhance plasticity properties and curing temperatures, preventing deformation during drying and firing (L. Anne, 2022).

As extensively explored thus far, the firing process is an indispensable phase in establishing chemical stability within the material, subsequently stabilizing its mechanical and physical attributes. In its greenware state, clay represents a pseudo-coherent material, with particle behavior influenced by cohesion, proximity, and hydration state. Ceramics, on the other hand, adopt a distinct crystal structure, arising from chemical alterations undergone by the tetrahedral lattice and oxygen atoms constituting the clay during extended exposure to exceedingly high temperatures.

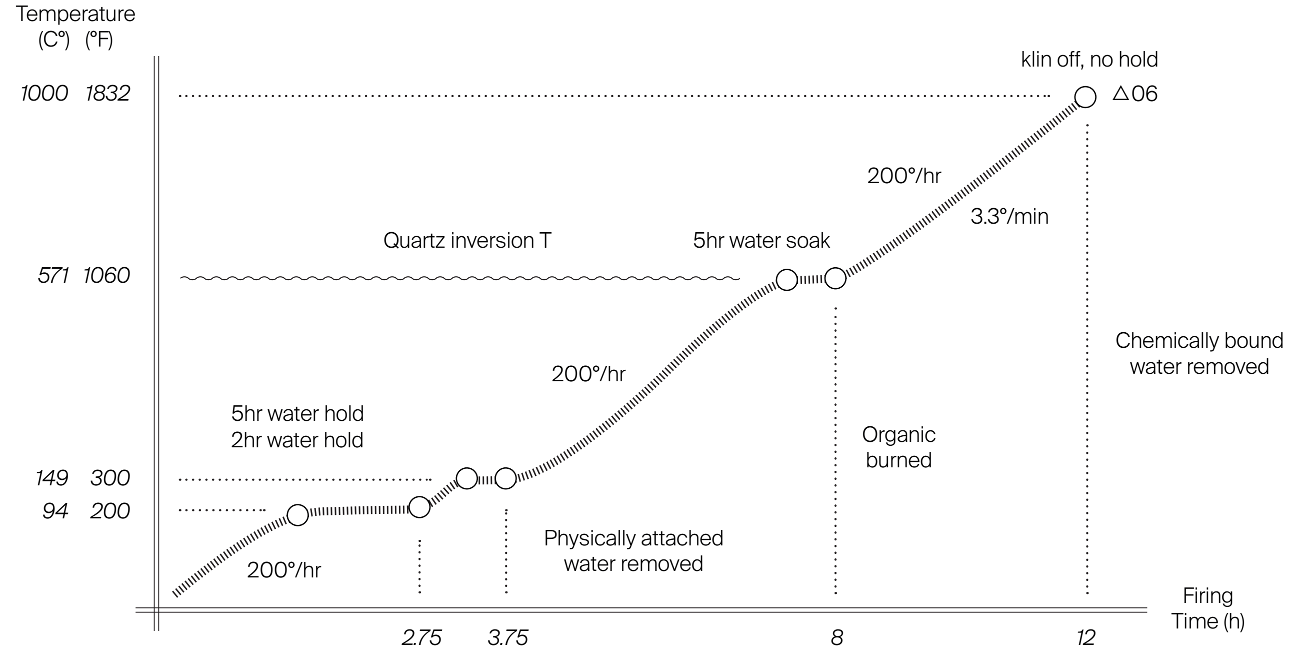
Linda Bloomfield (cited in Staff Reporter, 2022) highlights that among the transformations clay undergoes during the firing process, the initial step is the evaporation of residual water within the material. Despite prior drying of the artifacts, residual water often lingers between clay particles, necessitating removal before reaching firing temperatures to prevent steam formation and potential piece cracking or explosion. To address this, a preliminary drying phase, referred to as *water smoking* is conducted during furnace ignition, maintaining temperatures at approximately 80-100°C for several hours, allowing water in the clay crystals' pores to evaporate. Subsequently, the *dehydroxylation* stage ensues, involving chemical alterations that render the material incapable of binding with water molecules. This process occurs at temperatures exceeding 550°C and is irreversible, signifying that the clay can no longer return to a pliable state. Further firing at approximately 573°C results in a slight volume expansion of approximately 1 percent of the crystalline quartz present within the clay body, potentially causing cracking if kiln temperatures increase too rapidly. At this juncture, organic matter within the clay begins to degrade and oxidize into carbon dioxide, while substances like fluorine and sulfur dioxide are expelled, typically at temperatures ranging from 700-900°C, contingent upon the clay type. Once this phase concludes, the transformation from clay to ceramic is finalized, with the particles sintered or fused together, yielding artifacts robust enough to withstand handling and the subsequent glazing process.

When discussing ceramic firing techniques, a clear distinction is often drawn between oxidation and reduction processes. At the molecular level, both of these processes involve the removal of oxygen molecules from the lattice to which individual tetrahedra are bonded. These tetrahedra, as a reminder, are connected to three other tetrahedra through oxygen bridges. The presence of oxygen within these bonds is directly responsible for the clay's behavior, maintaining its pseudocoherent nature in the greenware state. Consequently, both oxidation and reduction methods result in the loss of oxygen atoms and the strengthening of bonds between the chains, causing the material to lose its plasticity, becoming rigid and no longer resembling water molecules. The key difference between these two methods lies in the mechanism responsible for removing the oxygen present within the bonds of the chains. This variation is due to the presence of different substances in the furnace environment that act as catalysts for these chemical reactions. As mentioned earlier, both the clay body and glazes interact with the surrounding atmosphere at the molecular level during the firing process. The oxidation technique relies on the presence of a substantial amount of oxygen inside the kiln during the firing of objects, a characteristic typically associated with electric kilns. Elevated temperatures cause the bonds in both the clay and glazes to break. These oxygen molecules present in the kiln come into contact with the surfaces of the objects and, owing to their high electronegativity, attract electrons from other substances, such as glazes and clays, resulting in oxidation.In contrast, the reduction process, distinctive to combustion furnaces, capitalizes on the accumulation of substances like carbon, hydrogen, and CO within the furnace. These gases are inherently unstable, and the absence of oxygen in the environment prompts them to seek an oxygen atom from an external source, eventually transforming into a more stable $CO2$ molecule. The removal of oxygen from metal oxides contained in glazes and clays by these gases leads to their reduction into their metallic form. The choice of firing mechanism, therefore, leads to different surface outcomes due to the specific firing method employed (Vesuvius Lab, 2014).

In general, it can be stated that the type of kiln used, and consequently the oxidation or reduction reaction it facilitates, defines the aesthetic characteristics of the artifact once its transformation into ceram-

CERAMIC FIRING PROFILE

Img.22
Bisque firing temperature profile with chemical changes highlithed. The initial step is the evaporation of residual water within the material, temperatures are maintained at 80-100°C for several hours. Subsequently at 550°C, the "dehydroxylation" stage ensues, involving chemical alterations that render the material incapable of binding with water molecules. Clay can no longer return to a pliable state. At 573°C occurs a slight volume expansion of approximately 1 percent of the crystalline quartz present within the clay body. Organic matter within the clay begins to degrade and oxidize into $CO2$, fluorine and sulfur dioxide are expelled, typically at temperatures ranging from 700-900°C. Once this phase concludes, the transformation to ceramic is finalized. Graphic design based on data from CAWstudiopotters, 2020.



^ Img.23, 24
^ Examples of different surface finishes of ceramic vases based on the firing cycles they have undergone. In the first image, the artifact, in its bisqueware state, presents a porous and rough texture. The material can still absorb water within the microporosities but is no longer able to chemically bind to it and deform plastically. In the second image, the object, in its glazeware state, exhibits a shiny surface due to the glaze applied during the second firing process. The glazed material makes the pot waterproof and suitable for fluid-contact applications. Unurgent argilla material archive, Nina Salsotto Cassina.

ics is complete. Various types of kilns are employed for firing clay, ranging from advanced solutions that allow precise digital control to DIY alternatives, such as brick kilns or pit furnaces dug into the ground. While electric and gas-fired kilns are the most commonly used today, wood-fired and pit furnaces continue to be employed as ancient alternatives (L. Anne, 2022). Each kiln exploits distinct principles and techniques, resulting in diverse types of artifacts in terms of surface finish and aesthetics due to the materials present and conditions within the kiln chamber. Electric kilns are the most commonly used by ceramicists. They are known for their ease of use and regulation through digital control panels. These kilns feature firing chambers lined with highly insulating and porous bricks. Embedded within the walls are metal coils through which high electric currents pass, serving as heating elements. The presence of these electrical elements limits the kiln's suitability to low and medium firing, as excessive temperatures could lead to the consumption and breakdown of the metal heating elements. Additionally, their design is incompatible with gas usage, making electric kilns operate in an oxidizing atmosphere and unsuitable for soda firing, a technique involving the application of a sodium bicarbonate mixture onto ceramics during firing. This firing technique creates unique effects on the finished pieces, but it is not safe to spray liquid into a kiln equipped with electric elements. Soda firing, on the other hand, is primarily performed in the second type of kilns, namely gas kilns, although they are less commonly used than electric ones. These kilns utilize the combustion of natural gas or propane to heat the chamber. The ratio of fuel to oxygen within the furnace determines how the objects are fired and how the flames interact with the artifacts. These kilns typically undergo reduction firing, where the carbon in the atmosphere removes oxygen from the clay. This process, influenced by the amount of gas present, alters the texture of the material and glaze, resulting in colors that are more intense and rustic compared to those obtained through the oxidation process. Wood-fired kilns offer an economically attractive option for those interested in constructing their own kiln by hand. They require the creation of a brick box and the use of firewood. However, firing pottery in a wood-fired kiln is a challenging process that demands significant time and effort, often spanning up to three days, with continuous attention required to maintain the fire and the right temperature through wood supply. Consequently, the use of these kilns often necessitates the presence of multiple individuals taking turns monitoring the firing, along with a substantial amount of fuel. This method, which relies on the interaction of objects with the live fire, can lead to some objects breaking during firing due to the movements of flames and burning wood. The unpredictability and natural effects of fire and ash are central to the creative process and represent the artistic component sought by those who use it. Similar to wood-burning kilns are kilns that utilize sawdust. In these kilns, objects are stacked in alternating layers with sawdust, and the burning rate of the sawdust can be controlled by regulating the amount of air fed into the kiln. Additionally, there are pit and barrel firing techniques that operate on the same principle but differ in the element used as the heat chamber either a pit dug in the ground or a barrel. These methods do not involve the use of a traditional kiln and represent some of the oldest ceramic firing techniques. In these techniques, pieces to be fired are arranged within a space separated by combustible materials like sawdust, wood, and leaves, creating multiple layers. The fuel is ignited and allowed to burn until exhausted, and then the objects are left to rest for a few hours. The entire setup is covered with sand or earth to create a reducing atmosphere and trigger the desired reaction.

2.2.2

Ecological footprint and emissions

Ceramics, despite its ancient lineage intertwined with humanity's progress across centuries, is now gaining recognition as an innovative material, finding new applications in the fields of medicine and engineering.However, from an overall perspective, looking at the many steps that lead clay to be transformed into ceramics, it seems fair to ask ourselves what is the burden of environmental impact that such a lengthy process drags behind it and whether it can therefore be called truly sustainable. From a theoretical standpoint, for a process to qualify as eco-friendly, it must adhere to specific criteria and parameters, as elucidated below (E. Layne, 2012): (1) First and foremost, it should preserve the Earth's natural resources and establish mechanisms to prevent their overexploitation. (2) The products of this process should be fashioned from sustainable materials, adhering to circular economy principles that minimize waste generation through reuse and recycling. (3) The energy required for production should be sourced from renewable, naturally regenerating sources. (4) Additionally, eco-friendly processes should effectively manage and dispose of waste materials that cannot be reintegrate into the production cycle. (5) Lastly, such processes should implement water-efficiency programs to reduce the consumption of essential water resources. Lesley Anne (2022) points out several reasons why ceramics are generally perceived as a fully sustainable alternative in the collective imagination. These include, first and foremost, the ease with which raw materials can be procured from nearly anywhere on the planet, reducing emissions associated with extraction and cross-border transportation. Furthermore, aside from raw clay and water, ceramics require no other natural material resources. Ceramics are celebrated for their versatility and durability, for their physical and chemical properties, which contrast with the production of disposable items born out of contemporary consumerism. Finally, proponents of ceramics as an environmentally sustainable material emphasize that once fired, ceramics do not release toxic or harmful chemical compounds into the environment during their gradual degradation, even if it occurs over centuries.

Despite these commendable attributes, ceramics, when assessed in alignment with Elizabeth Layne's criteria for eco-friendly processes, may not qualify as an environmentally sustainable material, particularly when contrasted with the design of modern industrial processes. While ceramics do possess ecological qualities, advocating for their unrestricted use within the context of current industrial practices may appear misleading at best. Indeed, while pottery originates from clay and other raw materials abundantly found in nature, it's important to recognize that the Earth takes centuries, if not thousands of years, to regenerate these raw clay deposits. These materials, aggregates composed of fine particles resulting from natural erosion over millennia, technically represent a naturally regenerating material. However, it must be acknowledged that human extraction and consumption of clay far outpace the Earth's regenerative rhythms. Furthermore, once clay is fired and transformed into ceramics, it undergoes irreversible chemical changes. Although ceramics are still considered naturally occurring, their capacity for reuse in the same manner as raw clay is diminished, essentially rendering them a de facto finite resource given their exceedingly prolonged regeneration times.

Ceramic tiles, in particular, constitute one of the most prevalent materials in the construction industry. According to the World Green Building Council (WorldGBC), the materials and construction processes employed in building construction contribute to approximately 11 percent of the world's total annual CO2 emissions. A significant portion of these emissions can be attributed directly to ceramics. For instance, consider the production of a ceramic tile, a versatile material used for wall and floor coverings, with a composition and manufacturing process akin to other widely used architectural elements such as bricks and tiles. The production of ceramic tiles involves several stages, including raw material extraction, material pulverization, powder drying, pressing and shaping, and finally firing and glazing. In the entirety of this process, approximately 80 percent of the total CO2 emissions generated are linked to the firing and drying phases (J. Peng et al., 2012). Consequently, ceramic tile production constitutes an energy-intensive process with substantial pollutant emissions into the atmosphere during heat treatment stages. The energy primarily used for firing clay comes from fossil fuels, the combustion of which contributes directly to environmental issues like global warming, acid rain, and the formation of harmful particulates (due to sulfur dioxide emissions) (L. Anne, 2022). The primary energy sources involved in the process include coal, diesel, and natural gas (J. Peng et al., 2012). Regardless of whether electricity, gas, or wood is used for firing, the process demands significant fuel consumption due to the elevated temperatures required for the transformation into ceramics, which can range from 800 to 1700°C. This inherently renders the process extremely energy-intensive, not to mention that a second firing cycle is often necessary when applying glazes to achieve a superior finish (L. Anne, 2022). While efforts have been made to recover the heat generated by kilns through systems that redirect it into buildings or export it to nearby communities, these practices, although beneficial in reducing the carbon footprint associated with this aspect of production, still impose substantial environmental costs in terms of resource utilization and the release of waste substances into the atmosphere. Achieving the necessary firing temperatures and the combustion of glazes, which frequently contain volatile toxic substances, yields harmful by-products that pose risks to both health and the environment. Typical emissions include water vapor (H2O), oxygen (O2), carbon monoxide (CO), carbon dioxide (CO2), sulfur dioxide (SO2), ammonia (NH3), and in some cases, chlorine and fluorine compounds, all of which are environmentally hazardous. These emissions also lead to significant wear and tear on furnace linings. In general, the most prevalent decomposition product generated during the process is CO2, resulting from the combustion and oxidation of organic substances present in clay (R. Toledo et al., 2004).

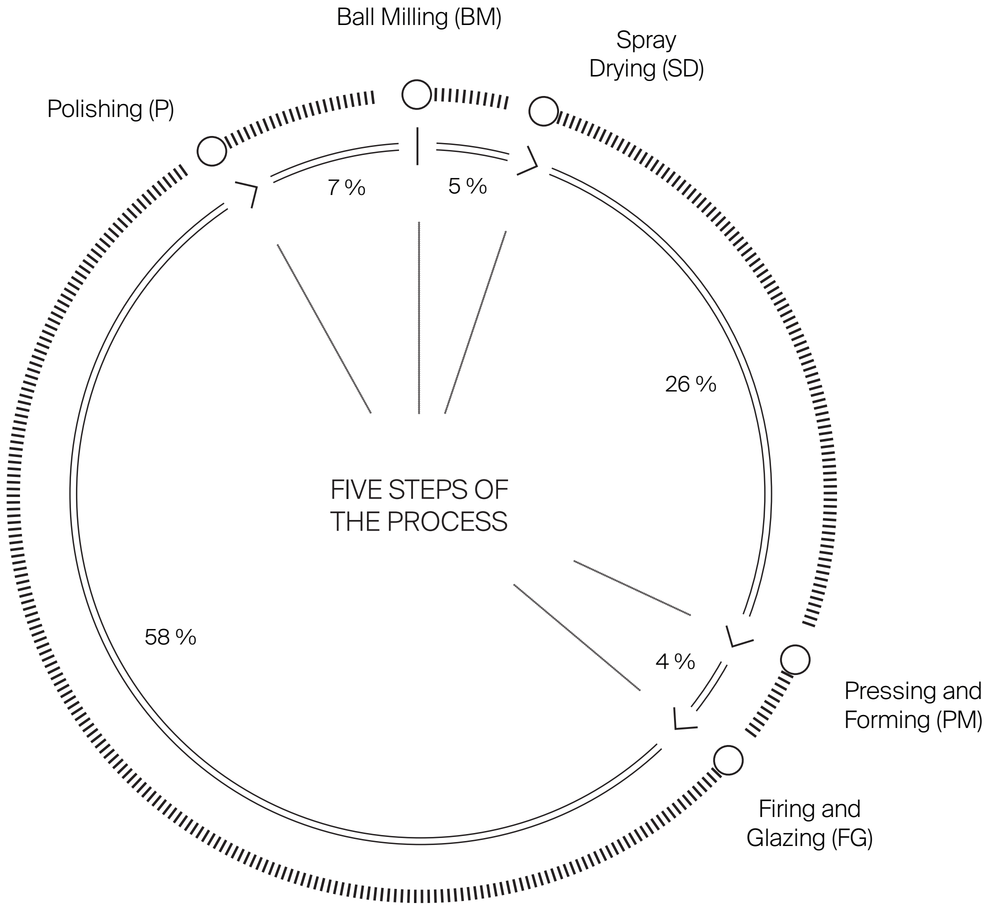
Apart from the exceptionally high service temperatures reached and the emissions produced during the ceramic firing process, a crucial factor to consider is that this cycle is reiterated whenever there's a need to enamel objects for waterproofing. A second firing cycle significantly amplifies the energy impact, leading to substantial fuel consumption and the release of additional gases and fumes into the atmosphere. Enamels employed in the ceramic industry often involve the use of chemical dyes and solvents that pose severe harm when released into the environment as waste (L. Anne, 2022). Typically, volatile substances generated during enamel firing are regulated and managed at an industrial level, with stringent guidelines in place for their filtration and proper disposal. However, this level of oversight cannot be guaranteed in artisanal production and hobbyist settings, where potters may not use professional ovens or may overlook regulations concerning enamel washing and groundwater pollution. Even though ceramic glazes necessitate lower firing temperatures than clay, they still reach temperatures of at least 900 °C, depending on the specific substances involved. The reason for these seemingly high service temperatures is that these compounds are designed to melt within the furnace and then solidify, creating a glassy surface layer on the object. Regardless of the volatile components and emissions generated during this second firing cycle, enamelled ceramic is unsustainable for additional reasons. One argument made by proponents of ceramics as an eco-friendly material is that once fired, it becomes inert and doesn't emit harmful substances during its degradation. Ceramic, much like stone, is an igneous rock that hardens over time and undergoes chemical decay due to weathering. However, the presence of an enamel layer significantly prolongs the natural degradation of the material. Atmospheric elements and agents that facilitate biodegradation cannot penetrate the protective enamel layer, extending the degradation process to potentially thousands of years, depending on the substances involved (L. Anne, 2022).

We have now outlined the processes of clay extraction, processing, and firing, highlighting the methods, tools, and emissions occurring throughout the cycle that culminate in the creation of ceramic artifacts. While ceramic is undoubtedly a versatile and durable material, presenting a more environmentally friendly alternative compared to materials like plastic and glass, it's evident that there are contradictions regarding its sustainability scattered throughout the numerous steps of the process. The key concerns raised by this analysis pertain to the environmental costs associated with the use of exceedingly high temperatures during repeated firing cycles, the emission of environmentally harmful and sometimes toxic substances, and the inability to reuse clay in its raw state once it has been thermally stabilized and transformed into ceramics. In the following subsection, we will delve deeper into greenware clay materials, introducing and exploring the potential for creating and applying biowaste clay composites.

SERVICE CYCLE OF CERAMIC TILES MANUFACTURING PROCESS

V Img.25
Contribution to total carbon dioxide emissions from each one of the 5 steps of the ceramic tiles manufacturing with *input materials* and source of energy involved in the different phases. Graphic redesign of the scheme in J. Peng et al., 2012.

Raw Material, Colour material, Additives, Electricity > BM
Material Slurry, Electricity, Coal, Diesel Oil > SD
Ceramic powder, Electricity > PM
Tile, Glaze material, Electricity, Coal, Diesel Oil, Gas > FG
Tile, Electricity > P



UNFIRED CLAY AND UBWCCS

2.3

2.3.1

The Moroccan Drâa Valley earthen architectures

In the section 2.1.2. titled *Eight stages of clay*, we defined the term *greenware* to encompass the various states of clay that have not yet undergone firing, irrespective of their composition or hydration level. Clay in its greenware state is inherently brittle due to the presence of oxygen within the chemical bonds forming its tetrahedral lattice structure. It resembles a pseudocoherent rock, and its mechanical properties are closely tied to its hydration state. In this stage, clay can still be manipulated by adding more clay or hydrating it to soften the material, allowing it to be reshaped. This characteristic makes it a 100 percent recyclable and reusable material. Typically, unfired clay is not used for crafting artifacts, except after firing and transformation into ceramics, which stabilizes it and enhances its mechanical and physical properties. Although unfired clay has limited applications, there are instances where it has been employed in specific fields like construction, particularly when stringent performance requirements need to be met. Unfired clay has been traditionally utilized in architecture, especially in rural areas where the abundance of clay resources, cost-effectiveness, and dry climate conditions favor its use. One notable example of such architecture can be found in the southeastern region of Morocco known as the *Drâa Valley*, stretching from the Saharan side of the High Atlas Mountains to the interior of the Sahara Desert. This region is home to a remarkable architectural heritage featuring structures constructed from unfired earth. Within the Drâa Valley, you can find over 300 *ksour* (Berber villages) and *kasbahs* (fortified houses) (E. Baglioni et al., 2013). In the architectural context of these buildings, earthen material plays a central role as the primary resource for constructing walls, floors, roofs, mortar, and plaster. The prevalence of clay in construction in this area is due to the abundant clay deposits of alluvial origin. The locally available *earth of the garden* has been a key factor in the sustained use of this material over the centuries. Various masonry techniques have evolved and been perfected in this region using clay materials, including rammed earth (known as *pisé* in French and *alleuh* in the local language) and *adobe* (referred to as *toub* in the local language), which are employed in different parts of the buildings (E. Baglioni et al., 2013).

Rammed earth, the first method, involves compacting earthen material through mechanical or manual compression within formwork. After compaction,

Img.26
A picture of the Ait-Ben-Haddou city, located in the Drâa Valley in the southeast of Morocco, near the Sahara desert and houses one of the greatest earthen architecture heritages in the World, consisting of ksur (villages) and kasbah (fortified houses). The building's walls are entirely realized with rammed earth and adobe techniques, employing raw clay materials. The roofs are made with palms wood structure and covered with canes and compacted earth.

the formwork is moved, and the process is repeated to create load-bearing walls and perimeters. This results in sturdy and durable elements capable of withstanding heavy structural loads. Wall thickness varies from 40-50cm for shorter buildings to 60-100cm for taller ones when employing this technique as foundations or lower masonry (E. Baglioni et al., 2013). Rammed earth mixture consists of a combination of clay (up to 30 percent), sand (50-80 percent), and lime (15 percent), with varying water percentages based on climate conditions, creating a mud mixture that holds its shape within formwork. Properly constructed earthen masonry exhibits good compressive strength and reasonable durability. This method, due to its simplicity and ease of material procurement, is ancient and dates back to the Neolithic period. It has been used across the globe, including South America, India, the Middle East, Africa, and even in the construction of parts of the Great Wall of China. In Europe, its use has been relatively limited, with examples primarily found in France and Spain (Designing Buildings).

The second construction method is adobe, which involves creating clay and straw bricks through molding and sun drying. In this method, the clay content is exceptionally high, and the bricks require an extended drying period, often up to a month, necessitating dry climates with moderate temperatures. These remarkably robust bricks can be further processed to achieve smooth surfaces, often coated with surface treatments. Lime plaster is a common surface coating choice, enhancing resistance to water exposure, thanks to its combination with straw. Unlike rammed earth, the adobe technique allows for controlled material shrinkage, occurring individually before construction, ensuring better resistance to cracks compared to a large monolithic wall (Solid Earth). The use of bricks also offers greater flexibility in shaping and permits the creation of openings in walls while facilitating easy replacement of damaged sections. In Moroccan earthen construction, adobe is primarily employed for constructing upper floors with lower loads, shaping unique architectural features that cannot be achieved with formwork, creating openings within structures, and repairing earthen masonry (E. Baglioni et al., 2013).

Rammed earth, used for building construction, is a relatively straightforward technique that offers the significant advantage of not requiring clay firing for structural formation. Walls constructed from clay materials possess numerous advantages, including strength, durability, fire resistance, biodegradability, non-toxicity, sound insulation, and excellent thermal properties. Specifically, unfired clay acts as a hydrothermal regulator, absorbing moisture from the environment and gradually releasing it in drier conditions. While crucial in dry climates like the Drâa Valley, this feature can result in continuous material expansion and contraction, ultimately leading to cohesion loss over time (E. Baglioni et al., 2012). In general, buildings made of unfired earth are particularly vulnerable to water and moisture infiltration, which can penetrate deeply into damaged surfaces. The continuous absorption and release of moisture cause material contractions that may eventually result in cracks, undermining structural stability. Wind erosion and sandstorms can accelerate wall degradation and disintegration through abrasive action on the material. To protect against weathering and reduce water infiltration damage, it is common practice to coat walls with a protective layer composed of lime. Lime serves as a natural stabilizer, chemically reacting with clay to make it impermeable and stronger upon drying. This protective layer acts as a sacrificial element that requires periodic renewal (typically every 4-5 years). Along with the presence of straw, it helps mitigate shrinkage and cracking due to weather exposure, playing a crucial role in stabilizing and safeguarding earthen walls in construction (E. Baglioni et al., 2012).

^ Img.27, 28
Deposition of the clay and straw mixture inside molds for the manufacture of adobe bricks. The proper compaction of the material is a key step to avoid the formation of defects during shrinkage and drying of the piece.

2.3.2

Unfired Bio-Waste Clay composites

In recent years, growing concerns about pressing environmental issues such as global warming, frequent natural disasters, and unsustainable resource consumption have sparked increased interest in alternative building materials like earth. While historically one of humanity's earliest construction materials, modern technological advancements and scientific research are reimagining its use in a contemporary, circular, and sustainable manner. The architectural wonders found in the Drâa Valley serve as a prime example of how deliberate material design phases and production processes can yield an exceptionally low environmental footprint. Clay inherently possesses significant circular potential, but currently, it contributes substantially to annual global CO2 emissions. Recognizing this, the scientific community has dedicated considerable efforts to devise various strategies aimed at enhancing the performance of raw earth materials. A prominent approach involves crafting material compositions by incorporating artificial stabilizers like cement, lime, synthetic fibers, and more. Cement, for instance, is widely employed in the construction industry due to its ability to meet stringent requirements and performance standards. However, while cement effectively stabilizes clay, it also entails substantial CO2 emissions. Notably, authors Nusrat Jannat et al. (2022) highlight how the use of artificial stabilizers compromises material sustainability by elevating embodied energy levels and impacting sustainability during the recycling phase.

To fully unlock their circular potential and circumvent these issues, the development of clay-based composite materials is increasingly shifting towards natural alternatives over artificial ones. The objective is to create stable, high-performing clay-based materials without resorting to artificial substances or firing. Consequently, the scientific literature is witnessing a growing trend in the utilization of natural fibers, agricultural waste, and bio-enzymes to adjust physical and mechanical properties. In some cases, particularly in economically disadvantaged regions, stabilizing clay soils involves native inert materials. For instance, in Papua New Guinea, volcanic ash is widely employed for this purpose (P. Zak et al., 2016). Research demonstrates that employing natural materials and agricultural waste as stabilizers in the production of unfired earth materials offers several advantages in terms of environmental benefits (energy conservation), cost-effectiveness, and ecological considerations (resource preservation) when compared to artificial substances (N. Jannat et al., 2022). Such approaches not only directly mitigate carbon dioxide emissions from clay firing processes but also serve as effective tools to reduce environmental strain by diverting agricultural waste from landfills. Additionally, the use of renewable sources for natural fibers presents eco-friendly, green resources that can open up new alternative economic opportunities for stakeholders in the agricultural sector (P. Zak et al., 2016).

This category of materials, primarily consisting of a clay matrix with a dispersed phase of natural origin, lacks a universally recognized scientific classification. Often, their classification hinges on the presence of unfired clay as a component. To categorize and reference these materials in this research, they will be referred to as *Unfired Bio-Waste Clay Composites* (UBWCCs). The predominant method of creating UBWCCs is through the adobe technique. Having explored and comprehended the processes described in previous sections that transform unfired clay into ceramics, as well as those leading to the production of adobe bricks, we can draw parallels between these processes and those related to UBWCCs. In particular, we noted that the production of ceramic objects involves numerous steps, beginning with raw material extraction and concluding with one or more firing cycles necessary to achieve mechanical and chemical stability. It's worth mentioning that approximately 80 percent of total CO2 emissions generated in this process stem from firing and drying alone (J. Peng et al., 2012). These processes also release various pollutants into the atmosphere due to the use of fossil fuels and the combustion of organic components in the clay and glazes. In contrast, the adobe brick production technique is markedly different, characterized by a low energy footprint, as it doesn't involve thermal processing cycles for the clay. Scientific literature indicates that the production of unfired clay bricks requires approximately 99 percent less energy compared to cement bricks (N. Jannat et al., 2022) and emits around 80 percent less CO2 into the atmosphere compared to ceramic bricks (D. Muheise-Araalia et al., 2021). Specifically, manufacturing a single fired clay brick results in the emission of 0.4 kg of CO2 and consumes roughly 2 kWh (N. Damanik et al., 2020). Moreover, UBWCCs have a considerably lower environmental impact during their life cycle compared to ceramic bricks. They can be easily recycled with minimal effort and low energy consumption, boasting an embodied energy of 0.45 MJ/kg, in contrast to the 3 MJ/kg for a fired earth brick (N. Jannat et al., 2022). To illustrate the disparity in energy between the two processes, consider that a one-square-meter wall constructed from fired clay or adobe generates approximately half the CO2 emissions and incorporates half the energy of a single ceramic brick. Consequently, a building constructed with fired bricks or concrete emits at least 1.7 times more CO2 and possesses over 1.5 times more embodied energy compared to its equivalent constructed with mud bricks (D. Muheise-Araalia et al., 2021). The use of fired earth bricks, in contrast to adobe equivalents, results in a significantly unfavorable impact not only from an environmental perspective but also in terms of energy, directly translating into additional economic disadvantages.

Img.29, 30
Throughout the project *The Decay of Belonging* (2017), Kate Studley aimed to discover a more sustainably conscious way of making art, reducing waste and considering the location as part of the artwork. Furthermore, to reconnect with her heritage, Studley decided to research the materials available to her from the farm she grew up on. By sourcing clay from her home and relocating it to Loughborough University, she hoped to reflect upon this personal journey between places. For the final presentation of the project, 3 large sculptures were presented in an outdoor space of Loughborough University, School of Art and Design. The installation was then subjected to external elements and left to grow and decay over a period of time. By relocating the land as a material, from the farm and presenting them as an art piece in another location she showed the movement of life as a process rather than as something fixed, in order to reflect her own movement. Conceptually, the work intends to show the beginning of something in one place and the end of it in another. The final outcome combined stones, straw, branches and clay in order to create a series of biodegradable sculptures (Future Materials Bank).

2.3.3

Tuning properties of UBWCCs

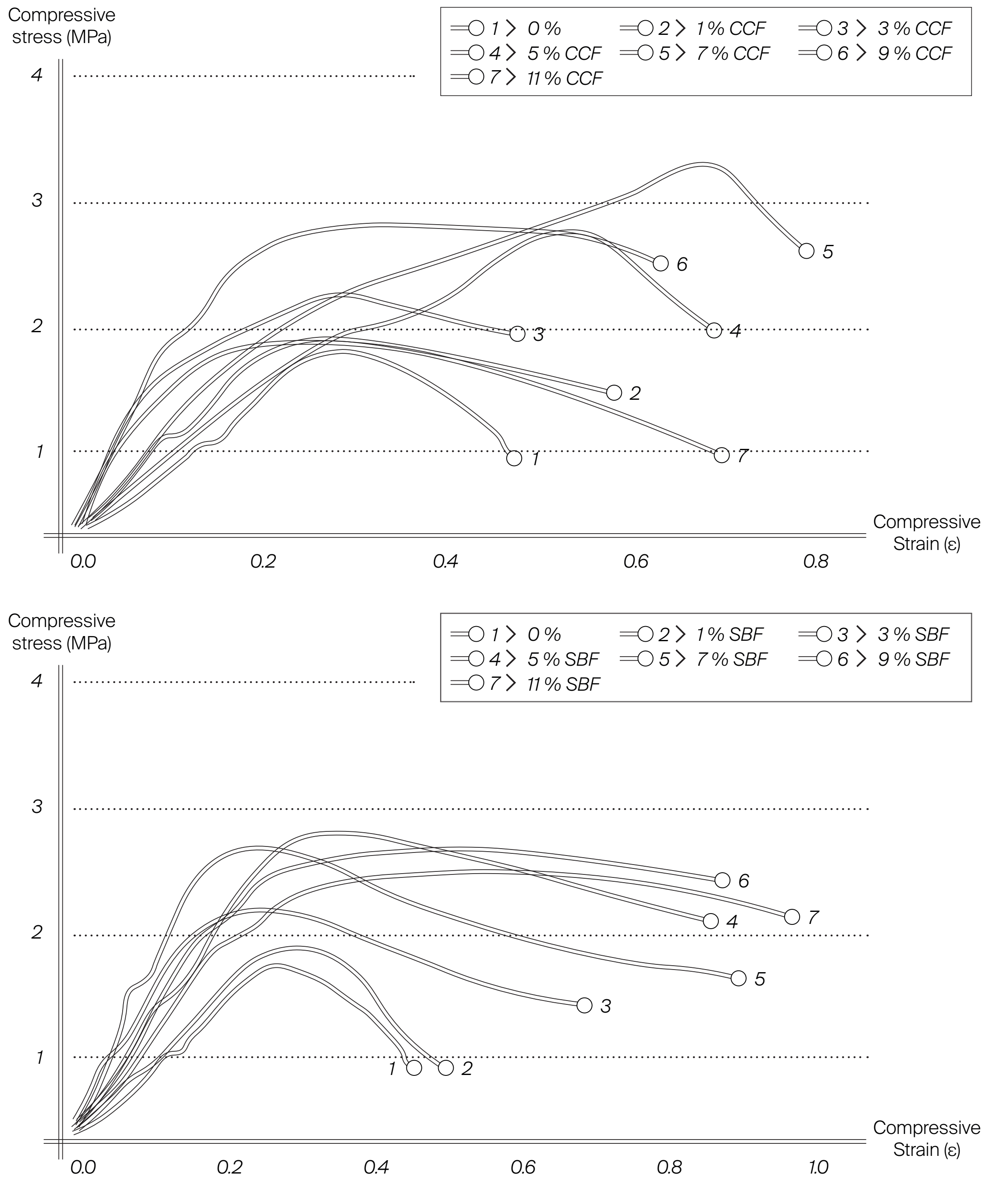
The examination of the physical and mechanical properties of UBWCCs typically involves conducting tests on material samples crafted using the adobe technique. This approach enables the collection of many empirical data regarding the impact of the dispersed phase on the material's physical and mechanical characteristics, including compressive and flexural strength, density, linear shrinkage, capillary absorption, water retention, and more. The introduction of waste-based additives derived from plants, animals, or other natural sources aims to enhance the mechanical properties of the composite by reducing shrinkage and improving strength and rigidity. Additional advantages associated with the production of raw clay composite materials primarily revolve around their low density and their ability to gradually release moisture into their operating environment. Moreover, utilizing waste materials represents an incredibly advantageous circular solution, especially if they are abundantly available locally, require minimal energy consumption, and have a minimal negative environmental impact (M. M. Salih et al., 2020).

Before comparing the behavior and performance of UBWCCs with raw clay and ceramics individually, it is essential to understand the physical and chemical changes that occur when a clay mixture incorporates a dispersed phase. Mahgoub M. Salih et al. (2020) emphasize that this process results in the formation of a fiber arrangement within the clay matrix, with fibers oriented randomly in space. The collective overlapping of these individual fibers gives rise to a network that interacts with the matrix, responsible for the *fiber bridging mechanism*. This mechanism entails the redistribution and transmission of stress throughout the composite material. Specifically, it leads to an increase in the material's compressive and tensile strength, along with greater resistance to crack propagation. The mechanical behavior of UBWCCs, as noted by the authors, hinges on the type of bonds formed between the material's phases, which can be categorized into three types: fiber-soil bond, soil-soil bond, and fiber-fiber bond. The strength of these bonds depends on factors such as the size of dispersed particles, surface conditions, and the quantity of fiber added to the clay matrix. The fiber-soil bond plays a pivotal role in transmitting stresses within the composite, making it the most significant contributor to the effectiveness of the fiber bridging mechanism. The soil-soil bond influences material density and porosity, thereby contributing to force distribution. In contrast, the fiber-fiber bond does not aid in force redistribution and represents the weakest of the bonds. Consequently, the proportion of the dispersed phase within the clay mixture dictates the type of bonds formed within the composite. Therefore, maintaining an appropriate balance between the phases is crucial for crafting a high-performance material. Excessive fiber content can lead to an increased prevalence of fiber-fiber bonds at the expense of mechanically beneficial bonds, ultimately diminishing UBWCC performance (M. M. Salih et al., 2020).

Apart from the load distribution mechanism described earlier, several other factors play a pivotal role in influencing the compressive strength of UBWCCs. These factors encompass the distribution of the dispersed phase, grain quality, clay mineral quality and quantity in the mixture, clay mineral binding strength, preparation process accuracy, compound homogeneity, water quantity, material compaction, and the use of supplements and additives. Collectively, these elements contribute to determining the material's density, which, along with fiber orientation in space, constitutes the two primary properties affecting mechanical behavior. On a microscopic scale, both clay and the dispersed phase behave differently during the mixing and drying phases. During material withdrawal, the evaporation of water can lead to increased porosity and the formation of cracks. This occurs because the matrix and dispersed phase undergo distinct drying processes, resulting in composite inhomogeneity. When clay particles are mixed, they interact with water molecules, causing the material to flow and preventing the formation of hydrogen bridges. This interaction determines the material's rigidity and resistance relative to its hydration state (P. Zak et al., 2016). Conversely, in the case of hydrophilic substrates like natural fibers, the dispersed phase may expand due to water absorption during mixing and exert pressure on the clay matrix during sample drying. As the fibers dry, they lose excess water and return to their normal size, leaving voids inside the matrix that shrink at varying rates. This leads to increased material porosity and decreased adhesion between composite phases (N. Jannat et al., 2022). Insufficient adhesion between the bonds formed during different stages can result in material defects that cannot effectively withstand stress. This causes the formation of stress peaks around the defects, ultimately leading to premature material failure. Although the dispersed phase has the potential to negatively impact composite density, effective integration has an overwhelmingly positive effect on material mechanical behavior. When properly oriented, fibers significantly enhance material ductility by altering its fracture behavior, enabling it to withstand greater stresses (P. Zak et al., 2016).

Up to this point, we have discussed the mechanical and physical impact of incorporating a dispersed phase into a mixture of clay soils to create UBWCCs. However, there are alternative approaches beyond simply adding substrates that serve the same purpose of enhancing the stiffness of raw clay composites. These approaches are rooted in the concept of Growing Design and involve the integration of living organisms into the material-making process. Novita Damanik et al. (2020) introduce the concept of a *bio-cementation process* through their experimental work, which harnesses the use of bio-enzymes as reinforcements to enhance the mechanical properties of UBWCCs. Bio-enzymes are natural, non-toxic liquids extracted from plants that react with the organic matter they come into contact with. These enzymes not only act on the natural substrate but also on the organic matter and minerals present in the soil. This reaction involves the microbes present in the soil, leading to binding and a reduction in the surface tension of the water within the sample. This promotes the penetration of moisture into the material, resulting in the compaction of soil particles. This phenomenon occurs as soil particles naturally fill the voids and cement together, increasing the composite's density. During their experimentation, Novita Damanik et al. created four types of UBWCCs, yielding a total of 30 different samples for each type. Specifically, the sample types were composed as follows: (1) Clay + water, (2) Clay + bio-enzymes, (3) Clay + water + sugar cane fibers, (4) Clay + bio-enzymes + sugar cane fibers. The experimental results demonstrate that as the composition changes, varying compression resistance values are achieved. The average compressive strength values for each type were as follows: (1) 3.92 MPa, (2) 4.26 MPa, (3) 5.5 MPa, (4) 9.14 MPa. This indicates that compared to the control sample A, which consists solely of raw earth, an improvement in mechanical properties is observed in all three types of samples: B, C, and D. The highest performance is achieved with

Img.31, 32
Compression stress-strain curves for unreinforced, chicken feather fibers reinforced (CFF) and sugarcane bagasse fibers (SBF) unfired soil bricks. Grapich redesign of the schemes in M. M. Salih et al., 2020.



Img.33
Avocado Seed Brick is a material innvestigation conducted by Fragmentario studio in 2023 about the re-interpretation of the traditional recipe for concrete that uses water, cement and sand. Instead of using cement, it proposes an expample of *bio-cementation* process by using alginate, a binder made from an extract of Sargassum, a macroalgae whose rapidly increasing presence in the Caribbean. The binder is created by mixing the alginate with water until creating a gel. Instead of using sand as an aggregate material, it proposes pulverised avocado seeds collected locally from a supermarket that is located 1.6Km away from the Fragmentario studio. The avocado-seed-dust is mixed with this gel to create the *Avocado Seed Adobe*, which is then inserted into brick moulds. The material is let to air dry during approximately a month (Future Materials Bank).

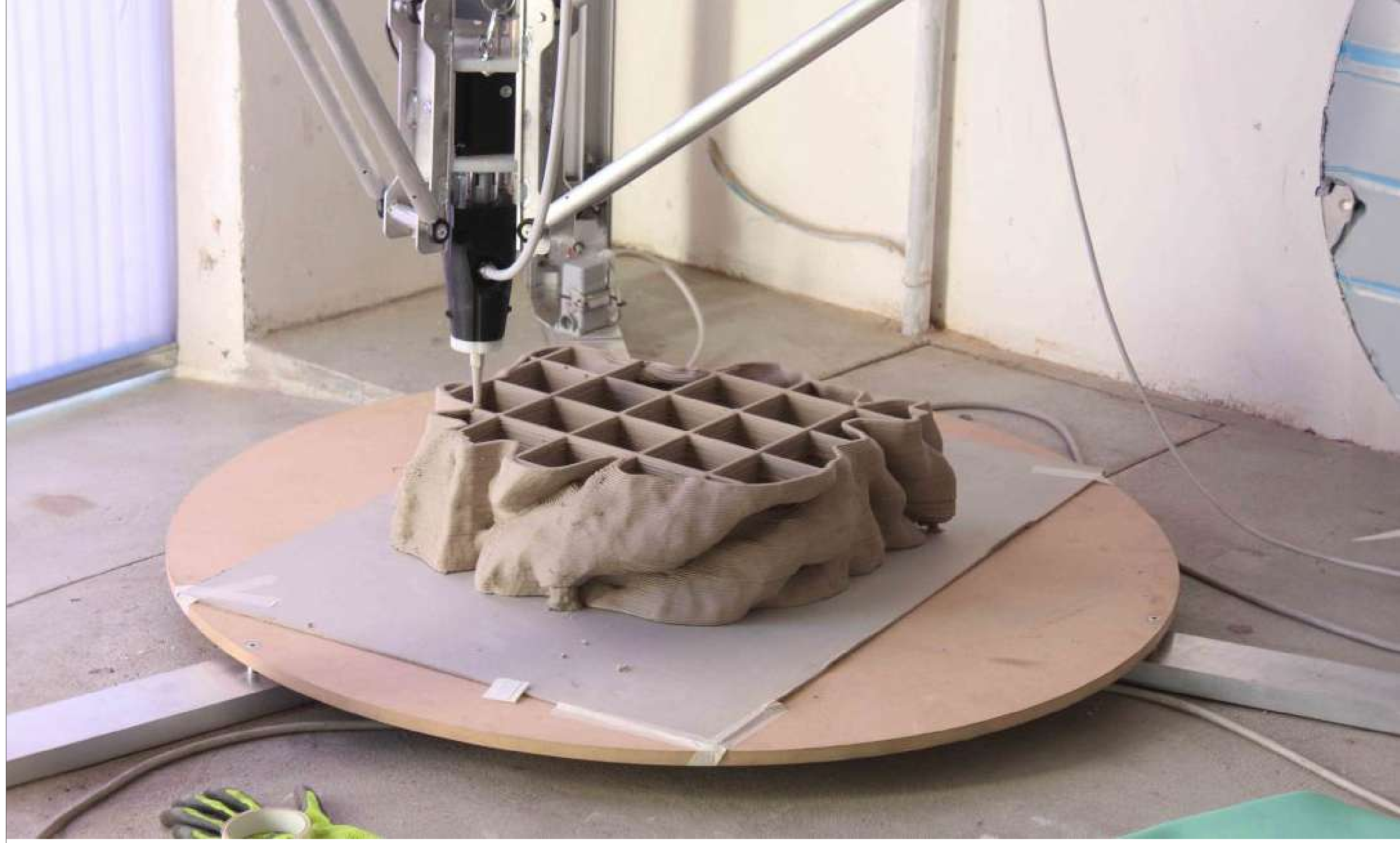
samples D, where both fibers and bio-enzymes are involved in the material-making process. In the research conducted thus far, we have compared the processes and environmental impacts generated by ceramic materials and UBWCCs. After conducting a thorough analysis of clay composite materials, it is possible to establish mechanical comparisons between them and their ceramic counterparts. It is evident that ceramic bricks, which are stabilized through heat treatments, exhibit superior mechanical resistance compared to raw clay and UBWCCs. Additionally, fired clay samples demonstrate better performance when it comes to factors like moisture, frost, and resistance to saltiness, as documented by D. Muheise-Araalia et al. (2021). Despite the significant differences between these materials, UBWCCs present a viable alternative to ceramic materials for various potential applications. A comprehensive understanding of both the microscopic and macroscopic behaviors of UBWCCs is essential to assess the factors influencing the physico-chemical behavior of these materials. Thoughtful design of material phases aimed at controlling properties is, therefore, a fundamental tool for achieving high-performance materials with minimal environmental impact. Raw materials offer environmentally friendly solutions that meet specific requirements, particularly in fields like construction, and their potential remains largely untapped. The increased use of UBWCCs and the realization of their potential would make a significant contribution to addressing current environmental challenges and further drive the adoption of circularity models that benefit all of humanity.

CLAY 3D PRINTING 2.4

2.4.1
Reimagining materiality

In recent years, clay has experienced a remarkable surge in its utilization within digital manufacturing processes. Thanks to its unique pseudo-consistent properties, clay materials are exceptionally well-suited for 3D printing through extrusion processes. Specifically, this 3D printing technology is known as liquid deposition modeling (LDM), which shares similarities with Fused Deposition Modeling (FDM) explained in the previous chapter, with the key distinction that material extrusion occurs at room temperature. Presently, additive manufacturing with clay materials incorporates 3D printing techniques akin to those used with plastic filaments. Notably, leading companies in the FDM sector offer the option to convert their filament printers into LDM models by integrating specific components like the pumping system and a dedicated extruder (J.A. Madrid et al., 2023). Clay 3D printing technology offers adaptable and highly customizable processes that seamlessly integrate into production workflows such as those found in fablabs, digital maker spaces, or small-scale private production setups. Furthermore, this technology's user-friendliness, recyclability, and reusability of material waste render it a more sustainable practice compared to FDM printing process. In contrast to FDM machines, which demand greater technical skills and knowledge for both model construction and the printing process itself and generate more waste due to printing errors, clay ensures complete reusability of the printing material as long as it remains in its greenware state.

In general, liquid deposition modeling (LDM) additive technology systems offer numerous advantages beyond sustainability. These include the ability to create intricate geometries with high print quality and the incorporation of features for assembling other components. LDM allows for the production of custom shapes and sizes tailored to project requirements and is conducive to the open-source approach, wherein users actively contribute to the design and construction of parts. Additionally, LDM systems tend to have relatively lower costs compared to alternative production technologies since they reduce the need for equipment such as molds and accommodate a wide range of production volumes without the need for significant scale to offset costs (A. Ascani et al., 2022).Despite its advantages, there are certain drawbacks associated with clay 3D printing, stemming from both the equipment involved and the characteristics of the materials used. It's important to note that the choice of equipment and methodologies varies from case to case depending on project objectives and requirements. One of the primary limitations relates to the achievable geometries. While clay 3D printing offers high precision and the ability to create intricate shapes that might be challenging with molds, it's essential to recognize that this technology follows a vertically oriented process. This orientation presents challenges when producing artifacts with cantilevered walls or ceilings. Additionally, the vertical orientation affects the material shrinkage phase, which occurs unevenly, primarily along the vertical axis, with variable percentages influenced by factors such as clay composition, temperature, environment, and additives. Another limitation arises from the fluid nature of the material, which prevents the creation of structural supports during printing. This lack of support affects the precision of certain types of connection features between pieces. While 3D printing offers the capability to replicate precise geometries infinitely, it may not be suitable for mass production due to time constraints and the utilization of machinery for producing one piece at a time (J. Keep, 2020). Among the main challenges there are potential defects resulting from the inaccurate loading of the machine. Filling the tank containing the clay mixture is a time-consuming and delicate process in which it is crucial to prevent the formation of trapped air bubbles inside the compound. Air bubbles can lead to defects during printing, causing interruptions in the material flow and violent bubble explosions when they reach the nozzle, resulting in surface defects (A. Ascani et al., 2022). Clay 3D printing is a relatively straightforward process, but it requires careful management of several variables that impact the process's success and the quality of the final artifacts. These variables include the preparation of geometries and print settings, such as layer thickness, base definition, model height, protrusion angles, wall inclinations, and layer overlap. Other technical considerations encompass the properties of raw materials, the condition of the clay mixture, environmental conditions, post-treatment, and material hardening (J.A. Madrid et al., 2023). Drawing from Jonathan Keep's insights (2020), we will now delve into specific technical aspects related to equipment, 3D modelling of the geometries, file processing and mixture preparation for the printing phase.



^ Img.34
Clay 3D printing is a form of additive manufacturing belonging to the cluster of LDM that utilizes clay as the printing material. It involves the layer-by-layer deposition of clay to create three-dimensional objects allowing for the creation of intricate, customized, and complex ceramic designs that might be challenging to achieve through traditional methods.

2.4.2

3D modeling, processing and mixture preparation

Extrusion-based systems are the most commonly used among all the methods for creating ceramic molded artifacts. Notably, pioneering digital manufacturing companies like WASP have significantly advanced this technology, providing accessible solutions for a wide range of users. In these printers, a pressure system or gravity casting is employed to extrude clay material through a nozzle, depositing it layer by layer along a controlled path to form the desired geometry. In the case pressure is required to propel the material through the machine components, it can be generated through either air or mechanical compression.

The process begins with the preparation of the clay mixture, which is then placed inside a tank featuring two chambers separated by a disc. One chamber contains the material, while the other is filled with air. As the pressure increases in the air-filled chamber, it progressively forces the material out from behind the disc and into a pipe that connects to the extruder. Within the extruder, a rotating screw compels the material to pass through a nozzle, where it is precisely deposited along the designated path. The nozzles themselves are constructed from durable metal materials capable of withstanding the abrasive nature of the clay mixture as it flows through. The nozzle plays a critical role in the printing system, as its size dictates the print quality and the level of detail achievable. Nozzle size varies based on the printing scale and significantly influences factors such as layer height, wall thickness, corner sharpness, and material flow. Implementing printing bases is a highly practical strategy for ease of handling and removing the piece upon completion of printing, allowing for separate management during the drying phase. To aid in the drying process and facilitate piece detachment, it is recommended to use printing bases made of porous materials. Additionally, maintaining a consistent base size helps avoid the need for frequent recalibration of machine coordinates.

The processing phase of a digital model, along with the construction approach tailored to the process, not only influences the quality of the artifact but often determines the success or failure of the print itself. Creating a 3D model for Liquid Deposition Modeling (LDM) printing differs significantly from Fused Deposition Modeling (FDM). In the context of clay printing, it's crucial to recognize that traditional supports, as used in FDM systems, may not be feasible. The structural support generated by file processing programs is often incompatible with clay, necessitating adjustments to the geometries to enable proper printing. One common strategy is to print pieces upside down when dealing with flared walls, but this can conflict with the desire to create objects with a stable bottom. An alternative is to use solid supports made from different materials, which can be removed after the piece has dried. However, this approach has limitations, as controlling the detachment of the piece from the support without compromising print quality can be challenging.

When creating a 3D model for LDM printing, it's essential to consider that the thickness of the walls is determined by the nozzle size and the volume of extruded material. Although the nozzle's material deposition creates a line slightly wider than the nozzle's outlet hole, modeling the object to align with these characteristics is necessary for creating double walls or specialized welding joints by intersecting the walls. Wall thickness also affects layer height, typically maintaining a 1:3 proportion, where the layer's height is approximately one-third of the vertical walls' height. This correct proportion ensures print stability and minimizes the risk of collapsing, especially for objects with tall or recessed walls. When constructing an object's bottom, attention to detail is vital. To achieve a well-constructed bottom, at least 2-3 layers are required, with machine paths working in a crosswise manner. Proper material flow balance between walls and the bottom prevents defects and cracks during removal. Infill addition, managed within file processing software, can become messy when using clay materials, unlike plastics. Clay mixtures are less stable and more prone to deformation and cracking during shrinkage and drying. To mitigate this, it's advisable to print double-walled objects when infill is present. This results in a clean exterior surface while the interior remains discontinuous due to the infill. The processes of infill addition and bottom creation are handled within slicing programs, which convert 3D models, typically in *.stl format, into *.gcode. *.Gcode is the computer language used by 3D printers and CNC machines to create a path for building objects layer by layer, using numerical control instructions. This language provides essential information, including XYZ coordinates, movement speed, and the activation of electronic/motorized components such as extrusion and fan control. While 3D modeling software offers a visual interface, the underlying model is constructed as a computer code. This code must be translated into *.gcode, which instructs the printer on sequential coordinates, movement speeds, and material deposition rates for each layer.

The preparation of the printing mixture is a crucial phase in the printing process, and its proper execution significantly impacts its success. You can use commercially available clay in powder form or pre-mixed clays, depending on the type of object and desired mixture composition. The choice between these options depends on specific requirements. When working with clay powder, it is advisable to prepare the mixture days or even weeks in advance, allowing the clay to mature and thoroughly blend with water over time. This maturation process reduces the formation of lumps, which can negatively affect the material's homogeneity and result in defects in the final workpiece. Whether mixing is done mechanically or manually, it is influenced by environmental conditions, and adjustments in the hydration level of the mixture may be necessary.

In general, the clay used in 3D printing should have a malleable consistency, soft enough to flow smoothly inside the printer but dense enough to support its own weight during material deposition without collapsing. The mixture should have adequate moisture content without being excessively sticky or prone to quick drying. Achieving the right consistency can be challenging and depends on various factors. Environmental conditions, the initial state of the clay (dusty or not), and the type of clay used all play a role. Different clay types have distinct characteristics due to variations in their mineral composition and their ability to absorb water. Additionally, when adding reinforcing fibers or particles, consider that these elements also interact with water, potentially requiring an increased water content. The introduction of a dispersed phase, such as fibers, affects the fluidity of the mixture, reducing viscosity and making it prone to tearing due to variations in grain size, which can result in lower print quality. Due to the combination of these variables, there is no straightforward methodology to determine an ideal printing consistency. It varies based on specific circumstances, and the most effective approach is to gradually add ingredients to achieve a compound with the appropriate properties for smooth extrusion during printing while maintaining good mechanical characteristics.

2.4.3
Earthen strucures from IAAC and Wasp

Open Thesis Fabrication (OTF) is an initiative from the *Institute for Advanced Architecture of Catalonia* (IAAC), centered on additive manufacturing within the construction domain. This program's objective is to delve into the potential and creative possibilities of on-site 3D printing, fostering the development of new environmentally friendly prospects (A. Puleo, 2019). Within this endeavor, a collaboration between IAAC and WASP was born, with a focus on constructing self-supporting buildings using raw earth. This venture is situated within a context where the construction of structures in vulnerable areas, involving local communities into the process and utilizing waste materials, represents a crucial stride toward a fully sustainable and accessible architecture for the future. The adoption of Liquid Deposition Modeling (LDM) printing technology in the construction sector enables the creation of solutions utilizing local resources and labor while maintaining a high degree of customization and construction speed. Among the projects undertaken as part of this program are the prototype of a self-supporting masonry structure in raw earth with an integrated staircase and *Tova*, a building featuring walls constructed entirely from raw earth.

In the case of the former, beyond the technical challenges, the project's main design hurdle was integrating the secondary staircase structure with the primary clay-based structure. The project aimed to withstand substantial stress loads despite the natural properties of raw earth as the supporting material. The 1:1 scale prototype was produced using the Crane Wasp printer, and IAAC students and researchers employed computational models to design the structure. The entire masonry, including the simultaneous assembly of the staircase, took 40 hours to print and required over 2 cubic meters of material. The printing mixture consisted of clay and rice fibers, with the plant component acting as a dispersed phase to enhance the composite material's mechanical properties. The mechanical characteristics, as well as the performance of raw clay composite materials, result from meticulous geometry design and the printing path. These aspects allowed for the creation of self-supporting, voluminous structures capable of connecting with wooden elements supporting the staircase floor (V. Carlota, 2019).

The second project, *Tova* is a collaborative effort between WASP and IAAC, aimed at creating the first 3D-printed raw earth building in Spain at Valladaura Labs, Barcelona (Staff Reporter, 2022). In this case, the printing material mixture doesn't involve a dispersed phase but leverages other ingredients that serve as quality-enhancing additives. The building's masonry was crafted using a blend of clay and enzymes, which increased elasticity during printing and contributed to cementing the materials during drying. The roof of the structure is made of wood, treated with a protective plaster derived from aloe and egg white to ensure weather resistance. All the materials involved in the project, including clay, additives, and wood, were sourced within a 50-meter radius of the construction site, making this building a prime example of the sustainable and circular potential of digital manufacturing in relation to UBWCCs. The project's implementation resulted in near-zero emissions and embraced an on-site approach with minimal waste.

^ Img.35
The 3D printed earthen staircase project is developed by the collaboration of IAAC and WASP. The project is a remarkable example of innovative construction using composite raw clay materials and LDM technology.

These structures serve as exemplary case studies showcasing the material potential of UBWCCs. The outcomes underscore the importance of deliberate design choices, both in the technical execution phase of the prototype and in the preparatory studies of the project context and materials involved. Following the comprehensive theoretical analysis presented in the preceding sections concerning UBWCCs' potential, we observe a notable large-scale application of these materials in conjunction with a more sophisticated and high-performance digital fabrication process compared to traditional adobe construction. Consequently, the role of the designer becomes increasingly significant from the project's inception, emphasizing the necessity for a well-rounded education within this framework, where designers must deeply contemplate their work and professional responsibilities within the discipline (A. Puleo, 2019).

Img.36, 37, 38
Layer by layer deposition of the material mixture employed for the implementation of the *Tova* project composed of clay, aloe, egg white and enzymes coming from a radius of 50 meters from the construction site. The prototype was designed to demonstrate sustainable construction solutions for the design and architecture sectors in Spain and generated no waste during the construction process. The possible applications of this construction model are endless. In combination with other construction systems, it can generate innovative buildings and housing complexes that reduce the environmental impact that current construction entails.

Alonso Madrid, J., Sotorrío Ortega, G., Gorostiza Carabaño, J., Olsson, N. O., & Tenorio Ríos, J. A. (2023). 3D Claying: 3D Printing and Recycling Clay. *Crystals*, 13(3), 375.

Anne. L. (2022). 7 Pottery Firing Methods Commonly Used – With Images. *The pottery wheel*. 9 July [Online], Available at: https://thepotterywheel.com/firing-clay/ (Accessed: 9 May 2023).

Anne. L. (2022). How to Glaze Pottery at Home – With or Without a Kiln. *The pottery wheel*, 15 July [Online], Available at: https://thepotterywheel.com/how-to-glaze-pottery-at-home/ (Accessed: 25 May 2023).

Anne. L. (2022). Is Pottery Clay Eco-Friendly? – or is it Costing the Earth?. *The pottery wheel*. 9 July [Online], Available at: https://thepotterywheel.com/pottery-clay-eco-friendly/ (Accessed: 9 May 2023).

Anne. L. (2022). Types of Clay for Pottery – The 5 Main Types of Ceramic Clay. *The pottery wheel*. 9 July [Online], Available at: https://thepotterywheel.com/types-of-clay-for-pottery/#fire (Accessed: 9 May 2023).

Anne. L. (2022). The 8 Stages of Clay – An Amazing Journey from Dirt to Art. *The pottery wheel*. 2 December [Online], Available at: https://thepotterywheel.com/stages-of-clay/ (Accessed: 7 May 2023).

Ascani, A., Cipriani, L., & Bolzan, P. (2022). Parametric modeling for additive clay manufacturing as a vector for sustainability/circularity in design education, *15th annual International Conference of Education, Research and Innovation, Seville, Spain*, 7-9 November 2022, 4516-4524.

Baglioni, E., Rovero, L., & Tonietti, U. (2012). The Moroccan Drâa valley earthen architecture: pathology and intervention criteria. *Rammed Earth Conservation*, 21-23.

Baglioni, E., Mecca, S., Rovero, L., & Tonietti, U. (2013). Traditional building techniques of the drâa valley (Morocco). *digitAR-Revista Digital de Arqueologia, Arquitectura e Artes*, (1).

Carlota, V. (2019). WASP and IAAC create 3D printed wall with embedded staircase. *3Dnatives*, 10 April [Online], Available at: https://www.3dnatives.com/en/wasp-and-iaac-create-3d-printed-wall-with-embedded-staircase/ (Accessed: 23 August 2023).

Damanik, N., Susanto, D., & Suganda, E. (2020). The Compressive Strength of Unfired Clay Brick with Sugarcane Bagasse Fiber (SBF) and Bio-Enzyme Reinforcements. *International Journal of Technology*, 11(7), 1422-1429.

Designing Buildings [Online]. Available at: https://www.designingbuildings.co.uk/wiki/Rammed_earth (Accessed: 29 May 2023).

Encyclopedia britannica [Online]. Available at: https://www.britannica.com/science/clay-geology (Accessed: 7 May 2023).

Encyclopedia britannica [Online]. Available at: https://www.britannica.com/science/clay-mineral (Accessed: 8 May 2023).

Future Materials Bank [Online]. Available at: https://www.futurematerialsbank.com/material/avocado-seed/ (Accessed: 1 November 2023).

Future Materials Bank [Online]. Available at: https://www.futurematerialsbank.com/material/clay/ (Accessed: 1 November 2023).

Keep, J., Layer, S., & Height, S. S. Z. (2020). A Guide to Clay 3D Printing. Available at: https://wikifactory.com/@jonathankeep/guide-to-clay-3d-printing (Accessed: 8 August 2023).

Jannat, N., Al-Mufti, R. L., Hussien, A., Abdullah, B., Cotgrave, A. (2022). Influences of agro-wastes on the physico-mechanical and durability properties of unfired clay blocks. *Construction and Building Materials*, 318(2).

L. Anne. (2022). 3 Stages of Firing Clay – A Beginners Guide to Firing Pottery. *The pottery wheel*. 15 July [Online], Available at: https://thepotterywheel.com/stages-of-firing-clay/ (Accessed: 9 May 2023).

Layne, E. (2012). Making Manufacturing Processes Eco-Friendly, *Chron*, 30 January [Online], Available at: https://smallbusiness.chron.com/making-manufacturing-processes-ecofriendly-38937.html (Accessed: 18 May 2023).

Muheise-Araalia, D., & Pavia, S. (2021). Properties of unfired, illitic-clay bricks for sustainable construction. *Construction and Building Materials*, 268, 121118.

Peng, J., Zhao, Y., Jiao, L., Zheng, W., & Zeng, L. (2012). CO2 emission calculation and reduction options in ceramic tile manufacture-the Foshan case. *Energy Procedia*, 16, 467-476.

Puleo, A. (2019). IAAC and WASP: New 3D Printing Strategies Towards the Realization of Load-bearing Earthen Structures. *IAAC Blog*, 29 May [Online], Available at: https://iaac.net/iaac-wasp-new-3d-printing-strategies-towards-realisation-load-bearing-earthen-structures/ (Accessed: 23 August 2023).

Salih, M. M., Osofero, A. I., & Imbabi, M. S. (2020). Constitutive models for fibre reinforced soil bricks. *Construction and building materials*, 240, 117806.

Solid Earth [Online]. Available at: https://www.solidearth.co.nz/earthbuilding-information/building-with-adobe-brick-technique/ (Accessed: 29 May 2023).

Staff Reporter. (2013). How long does soil take to form?. *Soils Matter*, 29 August [Online], Available at: https://soilsmatter.wordpress.com/2013/08/29/soil-formation/ (Accessed: 18 May 2023).

Staff Reporter. (2022). Firing Clay: The Lowdown on the Ceramic Firing Process - The Process of Firing Pottery Explained. *Ceramic Arts Network*, 28 November [Online], Available at: https://ceramicartsnetwork.org/daily/article/Firing-Clay-The-Lowdown-on-the-Ceramic-Firing-Process#0 (Accessed: 9 May 2023).

Staff reporter. (2022). IAAC + WASP build Spain's first 3D printed housing prototype using 100% local materials and local labor, zero waste and almost no carbon footprint. *Global Design* News, 12 September [Online], Available at: https://globaldesignnews.com/iaac-wasp-build-spains-first-3d-printed-housing-prototype-using-100-local-materials-and-local-labor-zero-waste-and-almost-no-carbon-footprint/ (Accessed: 26 August 2023).

Toledo, R., Dos Santos, D. R., Faria Jr, R. T., Carrió, J. G., Auler, L. T., & Vargas, H. (2004). Gas release during clay firing and evolution of ceramic properties. *Applied Clay Science*, 27(3-4), 151-157.

United States Geological Survey [Online]. Available at: https://pubs.usgs.gov/info/clays/ (Accessed: 7 May 2023).

VesuvioLab. (2014). La cottura 11 - Ossidazione e Riduzione. *Cono9*, 3 October [Online], Available at: https://www.cono9.com/blog/la-cottura-11-ossidazione-e-riduzione (Accessed: 10 May 2023).

WASP [Online]. Available at: https://www.3dwasp.com/ (Accessed: 9 August 2023).

World Green Building Council [Online]. Available at: https://worldgbc.org/advancing-net-zero/embodied-carbon/ (Accessed: 18 May 2023).

Zak, P., Ashour, T., Korjenic, A., Korjenic, S., & Wu, W. (2016). The influence of natural reinforcement fibers, gypsum and cement on compressive strength of earth bricks materials. *Construction and Building Materials*, 106, 179-188.

CHAPTER 3

3.1 MEETING MYCELIUM

MYCELIUM BASED 3.2 COMPOSITES

3.3 TUNING MBCs PROPERTIES

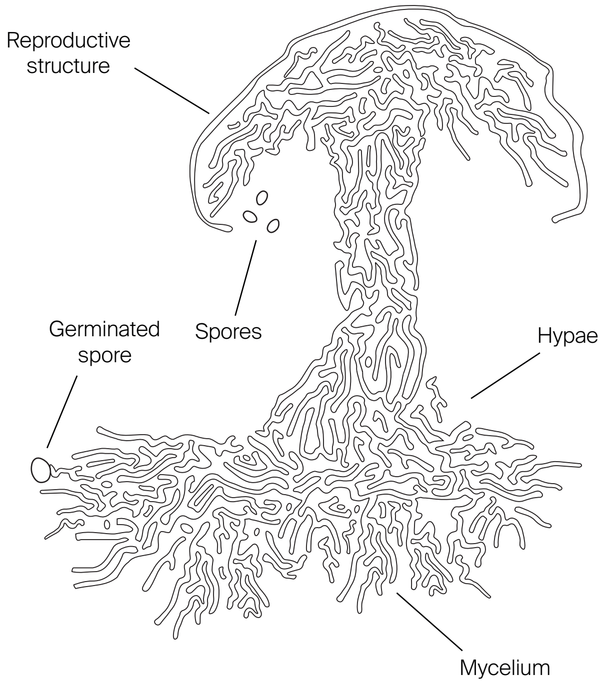
MYCO 3.4 CULTURES

... The term “mycelium” refers to the vegetative apparatus of fungi, comprising a fibrous mass of intertwined filaments called hyphae. It serves a central role in maintaining ecosystem equilibrium by decomposing organic matter in the soil and facilitating the absorption of water and nutrients by plants ... Mycelium acts as a natural self-assembling binder, fixing the fragmented composite in a monolithic form, creating a solid composite of cellulosic matrix biopolymers and very dense chitin reinforcements. Mycelium-based composites (MBCs) are thus agglomerates of defragmented lignocellulosic particles held together by a dense chitinous mycelium matrix that acts as a glue ...

Img.39

MEETING MYCELIUM 3.1

Img.40
Schematic representation of the fungal macrostructure, consisting of the mycelium and the organism's fruiting body.



3.1.1

A braided organism

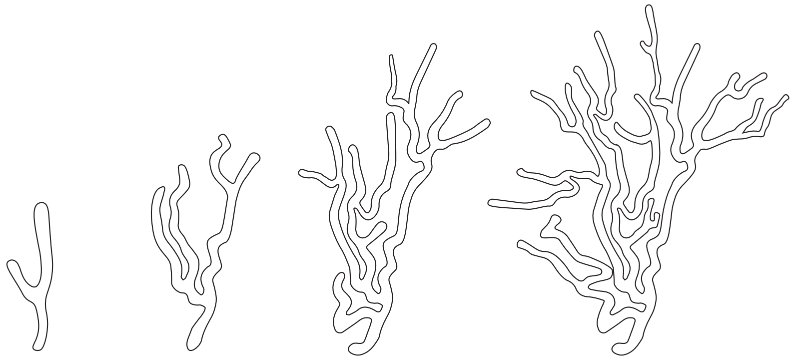
Fungi, also known as mycetes, encompass a diverse group of heterotrophic organisms reliant on carbon-based organic compounds for their sustenance (Treccani). The attention given to fungi is usually due solely to their role within the human diet. Not all naturally occurring mushrooms are edible, many species are poisonous, and still others have therapeutic properties. They exhibit remarkable adaptability, thriving in a wide range of environments, from forests and meadows to deserts and rocky terrain. This versatility underscores their crucial role in ecological equilibrium, contributing to soil microbial communities as decomposers, mycorrhizal mutualists, and pathogens (H. E. O'Brien et al., 2005). Fungi constitute their own distinct kingdom, comprising over 700,000 known species, including fungi, molds, yeasts, and truffles. While sharing certain characteristics with both plant and animal kingdoms, fungi are considered neither one nor the other, but rather are something in between but at the same time completely different from the two just mentioned. Mycetes are unicellular or multicellular life forms, consisting mainly of carbon and chitin. The main differences in the fungal kingdom compared to the animal and plant kingdoms are the following: the presence of a filamentous structure that makes up for the lack of differentiated tissues, a reproductive system characterized by spores that therefore does not rely on the presence of an embryonic system, the inability to carry out displacement or the process of photosynthesis. (A. Ghazvinian, B. Gürsoy, 2022).

Though we commonly associate fungi with the visible fruiting bodies found on the surface of multicellular species, their morphology is considerably more intricate than what meets the eye and primarily develops beneath the surface. The initiation of a new organism's growth commences with the germination of a spore, a minuscule reproductive cell originating from the cap of the fruiting body that emerges above ground. These spores are discernible only under a microscope and exhibit variations in color, size, and shape depending on the fungal species (A. Ogden, 2023). These spores disperse into the environment through various means, aided by weather conditions or animals. Once they land in a suitable environment for organism development, they initiate the formation of a dense filamentous network known as the mycelium. The term *mycelium* refers to the vegetative structure of fungi, comprising a fibrous mass of intertwined filaments called hyphae. Mycelium serves a central role in maintaining ecosystem equilibrium by decomposing organic matter in the soil and facilitating the absorption of water and nutrients by plants (International Online Medical Council). This mycelial network extends in all directions below the soil's surface and, when it reaches the surface, continues to grow above ground, giving rise to the fruiting body. The fruiting body is a fleshy structure that exhibits substantial variation in texture, appearance, and size across different fungal species. It can be subdivided into distinct parts, including the stem, cap, gills, and lamellae, with the latter serving as the site for spore production. These spores are subsequently dispersed to initiate the organism's reproductive cycle (P. Buchanan, 2007). In summary, spores, mycelium, and fruiting bodies represent distinct stages in the life cycle of fungi, each possessing unique structures and functions. Spores are generally responsible for fungal reproduction, while the mycelium constitutes the vegetative phase, tasked with nutrient absorption throughout the organism's life cycle, ultimately leading to the development of the structure responsible for spore formation and dispersal on the surrounding environment.

In addition to their role in nutrient supply, hyphae fulfill various other critical functions within the fungal network, including communication and information transport with both the surrounding environment and other parts of the network. These exchanges of nutrients and signals primarily occur underground or within other substrates conducive to the propagation of a single organism. Some species are limited to colonizing the soil's surface by invading leaves, fruits, and small branches, while others possess the ability to penetrate and influence diverse elements such as wood from large logs, animal droppings, or even establish close symbiotic relationships with living organic materials like trees and shrubs (M. Pizzulo, 2023). The remarkable capacity of hyphae to penetrate and thrive within various substrates, including decaying organic matter and living plants, allows the filamentous network to spread over vast areas. In fact, the largest known living organism on Earth is believed to be a specimen of the Armillaria ostoyae species, stretching across approximately 10 square kilometers in Oregon, USA, with an estimated age of over 2,400 years (A. Casselman, 2007). Although individual hyphae typically have diameters ranging from 1 to 30 μm, the overall length of the filamentous network can vary from a few microns to several meters. Hyphal growth initiates in an isotropic pattern, characterized by uniform growth without a specific directional arrangement. Subsequently, hyphae begin branching randomly and transition to a fractal, tree-like growth pattern. In this phase, individual branches interconnect through the

GROWING PARAMETRICALLY

Img.41
Schematic representation of the mycelium growth pattern. After an initial stage where the hyphae development follows an isotropic radial scheme, they begin to branch randomly, switching to a Fractal tree-like growth pattern.



process of *anastomosis*, where hyphal fusion occurs, forming a complex network of fibers (M.R. Islam et al., 2017). Moreover, beyond their role in nutrient exchange and structural growth, the mycelium, through hyphal fusion, plays a pivotal role in the reproductive aspects of fungi. When hyphae from two compatible fungal species meet and fuse, their cells combine, allowing their DNA to intermingle. This fusion results in the creation of new cells that produce spores, which can be retained within or exposed outside the organism's reproductive structures. This hyphal fusion phenomenon, under suitable environmental conditions, facilitates the sexual reproduction of fungi and the generation of new genetic combinations (E. Johnston, G. Brewer, 2023). Additionally, the minuscule size of hyphae enables the mycelium to efficiently distribute itself in three-dimensional space. Remarkably, a mere gram of soil can contain up to 600 kilometers of hyphae (M. Sydor et al., 2022) .

In their work, Islam et al. (2017) provide a microscopic definition of mycelium as "a biopolymer network where mechanical behavior is governed by the actions of individual filaments and their spatial arrangement within the network. When exposed to external forces, these individual filaments undergo rotation and deformation, influenced by their inherent elastic properties, orientation, and interconnectivity within the network. This leads to a complex, global network response." The response of this network on a macroscopic scale, which relies on the interplay of each individual fiber's reactions, can be attributed to its chemical composition. Mycelium primarily comprises extended natural polymer chains, mainly consisting of chitin, cellulose, and protein. Chitin, a complex carbohydrate found in fungal cell walls and the exoskeletons of arthropods like insects, spiders, and crustaceans, plays a crucial role within the mycelium. As a rigid polymer, chitin reinforces the cell wall against physical and chemical stresses, providing strength and structural integrity to the entire framework. It directly contributes to the resistance of individual filaments against internal osmotic pressure, external moisture, and mechanical strains (H. Muhammad et al., 2017). Chitin is intricately woven into the fabric of fungal biology, exerting significant influence on the organism's growth, survival, and ecological interactions with its environment. As previously mentioned, mycelium extracts nutrients from decomposed organic compounds, particularly plant-derived materials referred to as lignocellulosic materials. These materials predominantly consist of cellulose (30-50%), lignin (15-30%), and hemicelluloses (25-30%). Cellulose, the most abundant structural component in plant fibers, is composed of glucose chains that confer strength, rigidity, and stability to plants. Lignin, on the other hand, a complex polymer of aromatic hydrocarbons, contributes to plant structural rigidity by reinforcing cell walls and serving as a chemical binder between fibers (M. Sydor et al., 2022). During the decomposition process, hyphae infiltrate the substrate and release enzymes that break down complex organic molecules into simpler forms, including monomers that the fungus can absorb and utilize to develop. The capacity to degrade these substances varies among fungal species. Digafe Alemu et al. (2022) note that specific types of mycelium can degrade cellulose or lignin, secreting enzymes such as lactase, lignin peroxidase (Lip), and manganese peroxidase (MnP), while hemicellulose is typically susceptible to attack by all fungal species. Consequently, mycelium progressively spreads within the substrate, colonizing it, binding to the nourishing material, and forming an intricate network of branching fibers.

Img.42
Hyphal growth initiates in an isotropic pattern, characterized by uniform growth without a specific directional arrangement. Subsequently, hyphae begin branching randomly and transition to a fractal, tree-like growth pattern. Close up view from Gianluca Tabellini's work, Mycelium Tectonics, 2015.

Img.43
Close-up of the filamentous network of mycelium. Material sample from the “Mycelium Textile Project” by Jonas Edvard.

3.1.2

Connecting Nature

We have underlined the role played by mycelium in maintaining environmental equilibrium through the breakdown of organic matter and the reintroduction of nutrients into the ecosystem. The decomposition into smaller by-products not only serves as nourishment for the fungi themselves but also benefits the plants engaged in a symbiotic relationship with them. Just as mycetes can interconnect their networks with those of other organisms of the same or compatible species, they also possess the capability to do so with plant roots. Through mycelium, fungi establish a cross-network with plants, known as a *mycorrhizal network*, fostering a cooperative relationship (E. Johnston, G. Brewer, 2023), which extends its influence to 92 percent of plant families (Micropia-Amsterdam Museum). This network brings mutual advantages to all participants. Trees generate various nutrients, such as carbon-rich sugars and fats, through photosynthesis, which the fungi absorb. In return, mycelium collects essential resources like phosphorus, nitrogen, and water, distributing them to plant partners by extending their reach beyond the confines of individual plant roots. Furthermore, interconnection among organisms transcends the fungal-plant partnership, as neighboring plants connect with each other by binding to the fungus through the formation of mycorrhizal networks and utilizing it as a conduit. These linkages, where a single fungal organism connects multiple plant specimens, are referred to as *common mycorrhizal networks* (J. Gabbatis, 2020). The motivation behind fungi establishing such interconnections stems from the significant competitive advantage they gain by having a diverse array of partners from whom they can obtain carbon and nutrients. In this regard, mycetes are more reliant on their partners for survival, whereas plants can still extract nutrients from the soil even in the absence of fungi. However, this type of connection enables plants to share the nourishment they require with each other, creating a *social* framework in which various organisms collaborate during times of need. In this arrangement, so-called *mother* trees provide sustenance to struggling specimens. This intricate relationship between mycetes and plants suggests a perspective on ecosystems where individual organisms actively shape the environment around them. Due to the complexity and multitude of relationships among individual organisms, many scientists now view forests not merely as collections of individuals but as colossal superorganisms (J. Gabbatis, 2020).

MYCELIUM BASED COMPOSITES

3.2

3.2.1

Building with mushrooms

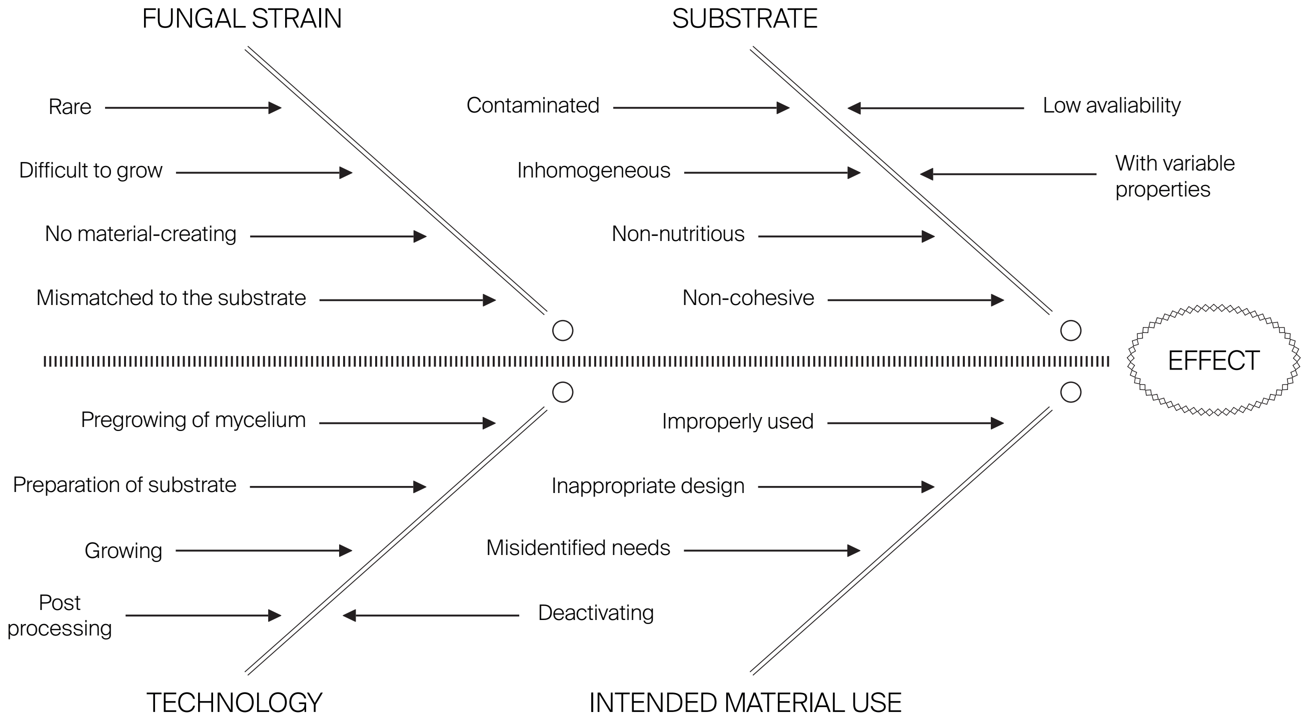
The degradation process performed by mycelium on a substrate leads to the growth of the organism's filamentous mass and its gradual densification overtime. As mycelium colonizes, it compacts the fungal mass with the substrate, enveloping and integrating it. This resulting product, an organic mass formed through mycelium growth, becomes a biomaterial based on fungi. These biomaterials can be categorized into two primary types: pure mycelium and *mycelium-based composites* (MBCs). Pure mycelium is obtained through the complete organic breakdown of the substrate, resulting in a soft mycelial mass with a relatively thick surface layer. This material is utilized in the production of vegan synthetic leather and biodegradable papers (A. Ghazvinian, B. Gürsoy, 2022). On the other hand, MBCs represent materials where the organism's growth is arrested at a certain point, forming multiphase agglomerates of lignocellulosic particles bound together by a dense chitinous mycelium matrix, serving as a natural adhesive (W. Sun et al., 2022). MBCs consist of two phases: a *binding agent* (mycelium) and a *filler* (substrate). The substrates have two main roles in this bio-composite creation process: they act as a dispersed volumetric component of the material and provide nutritional support for the organism's growth.

Frequently, in the pursuit of enhancing the production of MBCs, a variety of substrates with differing compositions can be utilized to enable the optimal execution of both filling and feeding tasks (A. Ghazvinian, B. Gürsoy, 2022). Through the integration of diverse Biofabrication techniques, it becomes possible to attain a range of distinctions in the morphology and mechanochemical properties of MBCs. Key factors influencing the physicochemical properties of these composites include the fungal strain type, substrate choice, and the methodology and technologies employed during fabrication and cultivation. This process's versatility allows for the creation of a wide range of materials, from synthetic skin using pure mycelium to composites such as foams, hot-pressed panels, or three-dimensional volumes through in-mold cultivation when mycelium is combined with an organic substrate (D. Alemu et al., 2022). Since the early 2000s, pioneering companies like Ecovative and Mogu have commercialized mycelium as a composite material, inspiring designers to explore microorganisms potential in manufacturing technologies that advance environmental sustainability. MBCs resemble dense, lightweight, biodegradable foam and have gained significant interest in industries like construction, packaging, soundproofing, art, and design. These materials are 100 percent biodegradable, independent of fossil fuels, renewable, and produce no waste during their lifecycle. In fact, their environmental impact can even be carbon-negative because mycelium, by consuming biomass-based substrates, sequesters carbon, preventing CO2 release. This repurposes waste materials and results in rapid, cost-effective, and energy-efficient production compared to other biomaterials (Marcus Fairs, 2021). Cultivating mycelium for MBCs production requires less energy and resources than producing synthetic materials, and it supports circular strategies by using locally available materials, including waste and by-products, as substrates to nourish the mycelium (Digafe Alemu et al., 2022).

However, there are more specific advantages associated with MBCs that stem from the ability to finely tune their characteristics through targeted interventions in the production process. When optimal organism growth is achieved, these materials exhibit remarkable properties, functioning as superb acoustic and thermal insulators. They are capable of retaining more heat than traditional fiberglass insulation, are fire-resistant, non-toxic, partially resistant to mold and water, and pound for pound, possess greater mechanical strength than concrete (Fisher A. in Marcus Fairs,

DESIGNING THE PROCESS

Img.44
Factors affecting the manifacture and use of MBCs. Graphic redesign of the scheme in Maciej Sydor et al., 2022.



2021). These composites maintain an extraordinary lightweight quality, despite having a dense filamentary network that ensures their robust mechanical strength. The mechanical behavior of MBCs is attributed to the fiber bridging mechanism, a principle described in the subsection *2.3.3 Tuning properties of UBWCCs*. This principle involves the redistribution and transmission of stresses throughout the composite material, particularly due to the physical interaction between the individual dispersed particles and the matrix. Similarly, in the case of MBCs, mycelium and the substrate interact to jointly resist external stresses placed upon the material. We will later delve into the specific analysis of the mechanical behavior of MBCs, emphasizing the primary factors influencing its regulation concerning material composition, growth, and processing.

Another unique characteristic of mycelium is its capacity to act as an active binder, not only within the relationship between the matrix and dispersed phases but also between two distinct fungal matrices. In this context, when two separate MBC artifacts containing live organisms come into contact, they continue to grow, binding together through a process known as *bio-welding*. This property of mycelium can be elucidated at the microscopic and chemical levels: the outer layer covering fungal hyphae consists of proteins and glycoproteins, controlled by *adhesive receptors* that govern recognition and adhesion to other cells by acting as an adhesive (S. Steudler et al., in W. Sun et al., 2020). The bio-welding property has been explored by authors like Wenjing Sun et al. (2020), who observed differing hyphal development in the substrate colonization process. The outer filaments exposed to air constitute the *top surface* (T), characterized by relatively low hyphal density and a soft, visually filamentous texture. In contrast, the inner matrix is highly dense and uniform. In their experiment, the authors grew a mycelial skin layer on a veneer sheet as a substrate, specifically chosen to separate the fungal layer from the wooden layer after growth, allowing independent testing of the former's adhesive properties. During the growth phase, the filaments exposed to air were referred to as the top surface (T), while those in contact with the veneer were referred to as the *bottom surface* (B). Subsequently, the mycelium layer, once removed from the substrate, was placed in contact with two new, undegraded veneers: one in contact with T and the other with B, to evaluate their adhesion. The experiment yielded positive evidence regarding the potential use of the mycelium layer as a standalone adhesive for bonding natural and untreated wood surfaces. Furthermore, it was demonstrated that the varying hyphal densities on the B and T surfaces impact the layer's ability to adhere to wood. Specifically, the lower, denser, flatter, and more hydrophilic surface displayed superior adhesive properties when tested against both lignocellulosic materials and the mycelium itself.

Img.45
Close-up view of the outer layer of an MBC with the organism spreading across the surface. Formation of an inconsistend and non-uniform chitinous matrix due to contamination and infection. Sample by LVDW Atelier.

3.2.2

MBCs cultivation process

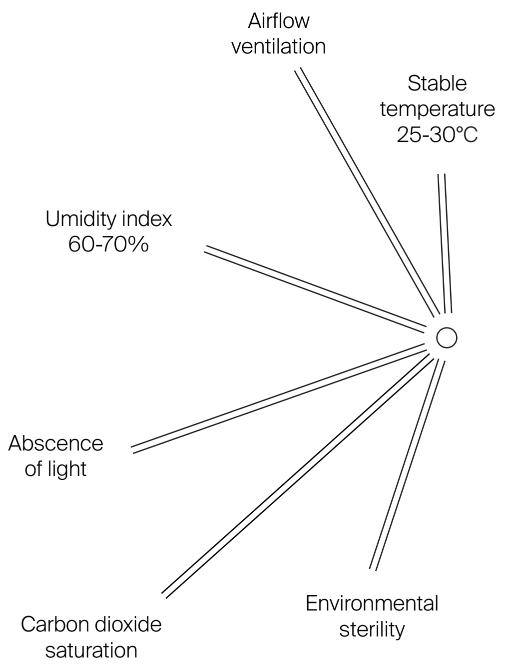
In line with the findings of Digafe Alemu et al. (2022), the manufacturing process for creating an MBC can be delineated into six primary stages: (1) cultivation of the fungal strain, (2) hydrating and sterilizing the grain (spawn), (3) inoculating the final substrate, (4) moulding, (5) deactivation, (6) transportation. Let's see briefly what these steps consist of.

(1) Cultivation of the Fungal Strain: This initial step involves culturing the selected fungal strain, which can be accomplished through either liquid culture or petri dish cloning. A detailed exploration of both techniques will follow in a dedicated subsection. The objective of cultivation is to isolate early mycelium strands and establish conducive conditions for the organism to flourish and replicate extensively before colonizing the final substrate. To achieve this successfully, the fungus must have developed resistance to contamination and already secured an advantage over competing organisms. Environmental conditions play a pivotal role in fostering mycelium growth throughout the process. The optimal microclimate for organism proliferation encompasses sterility of the surroundings, equipment, and ingredients used at all stages, a consistent temperature maintained between 25-30°C, constant humidity between 60-70%, an accumulation of CO2, and the absence of light. While specific temperature and humidity values may vary among different fungal strains, deviations from the recommended range can result in slow or nonexistent mycelium growth.

(2) Hydrating and Sterilizing Grains (Spawn): Following the initial culture, which typically spans at least seven days, the culture is employed to incubate *spawn* grains that have been hydrated and sterilized. This intermediate stage enables the organism to access a highly nutritious substrate while initiating substantial growth. Once the spawn is colonized, it is prepared to infect the previously sterilized final substrate. The granular nature of spawn facilitates the capillary dispersion of individual grains within the substrate, expediting the colonization process. The quantity of inoculum (spawn percentage relative to the substrate), along with the strain's growth rate and the substrate type, significantly influences the effectiveness and pace of colonization. The ideal inoculum quantity can vary from 3 to 20 percent of the total dry weight of spawn and substrate. An appropriate inoculum amount serves as a valuable tool in mitigating contamination risks. Increasing the

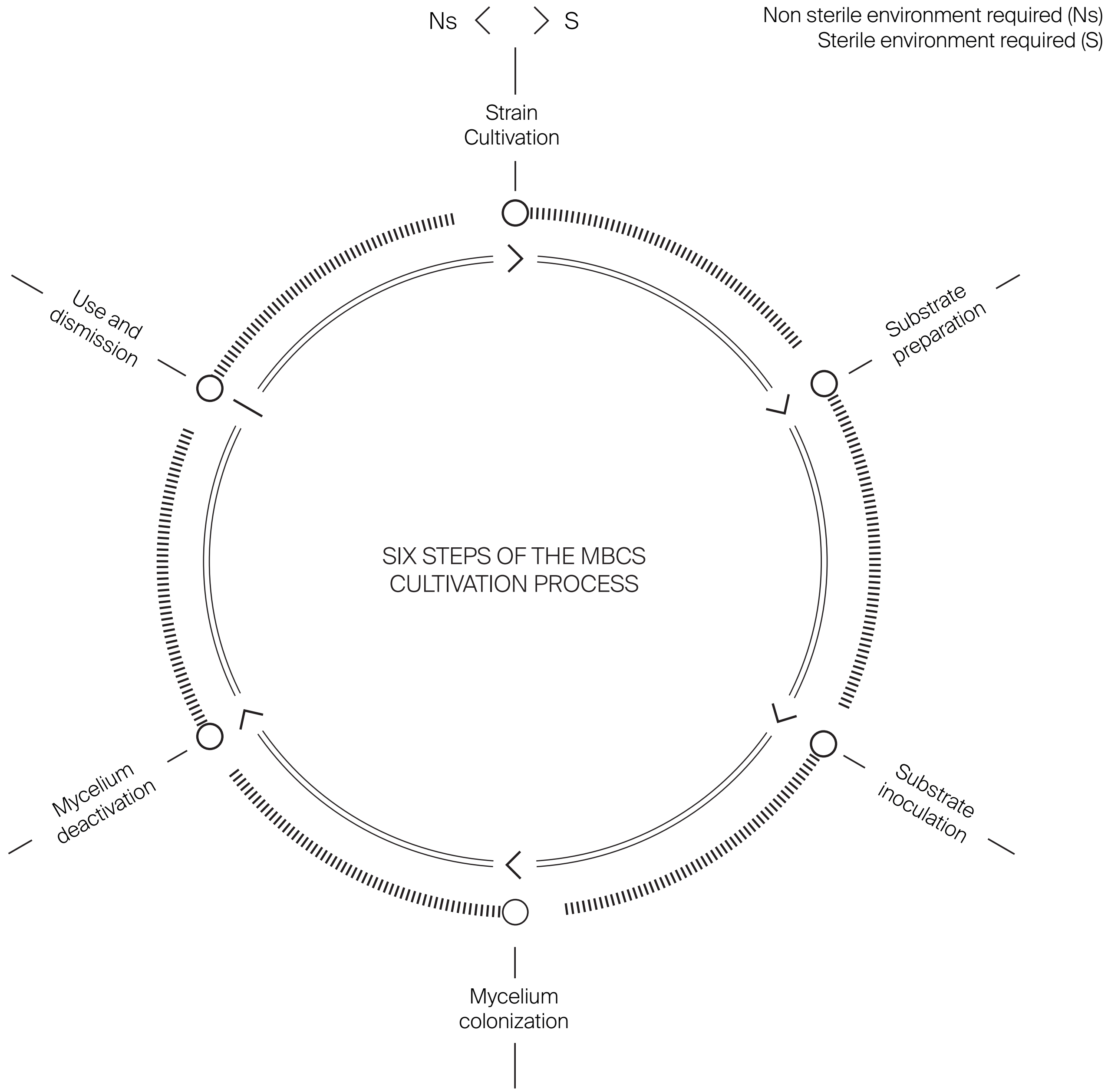
IDEAL GROWTH CONDITIONS

Img.46
Main environamental factors affecting the substrate colonization phase in the MBCs manufacturing process. Grapich design of the data in Digafe Alemu et al., 2022.



FROM TISSUE TO COMPOSITE MATERIAL

Img.47
Six main stages of MBCs cultivation and manufacturing processes. Cultivating the fungal strain involves isolating early mycelium strands and creating optimal conditions for growth, demanding sterility, 25-30°C temperature, 60-70% humidity, and CO2 accumulation. Hydrating and sterilizing grains produce spawn, crucial for infecting the final substrate. Controlling inoculum quantity (3-20%) mitigates contamination risks. Substrate inoculation requires monitoring pH, water content, and mycelial growth. Moulding with careful gas exchange regulates CO2 levels for growth and texture formation. Deactivating the organism through controlled temperature (100-120°C) or drying inhibits growth and ensures non-toxicity for safe use. Grapich design of the data in Maciej Sydor et al., 2022.



Img.48
Full colonization of the final substrate performed by the mycelium, ready to be used for the fabrication of MBCs. Generally, during substrate colonization, other phenomena related to mycelium growth occur: a slowing down of the substrate's ability to disperse water as moisture because pore size decreases and water retention through capillary action increases, an increase in nitrogen concentration, and a decrease in substrate pH. Jonas Evdard archive.

quantity of spawn used accelerates mycelium growth and reduces the likelihood of contamination. This is due to the larger area covered by mycelium on the substrate and reduced exposure time to contamination opportunities. Nevertheless, an excessive amount of spawn can impact the final physicochemical properties of the composite.

(3) Inoculating the final substrate: The quality of mycelium growth can be evaluated during this phase by assessing physical and chemical parameters such as visual inspection, artifact weight, pH levels, water content, and the surface finish morphology of the material. A desirable MBC should feature a thriving organism and a substrate with lowered pH due to degradation, along with elevated levels of nitrogen and water. Healthy growth is characterized by the formation of a dense, soft mycelial layer on the material's surface. As previously mentioned, mycelium possesses the remarkable ability to grow within the gaps between substrate particles, forming a dense chitinous matrix that fills all available spaces. During its growth, the organism assimilates the substrate and consolidates it into a compact mass, which can be shaped into specific three-dimensional forms.

(4) Moulding: Employing a mould in this context offers an excellent solution for precise control of shape and replicability. When the final phase of organism growth occurs within a mould, the resulting mycelial matrix faithfully reproduces the dimensions defined by the mold's walls. However, when manufacturing MBCs using a mold, one crucial factor significantly influences the process's success: the exchange of gases between the organism and its surroundings. By using a mold, conditions are created where the mycelium, enclosed by the matrix's walls, consumes oxygen and generates an accumulation of carbon dioxide (CO2) inside the mold. An environment saturated with CO2 is essential for the process, but the organism also requires a fresh supply of oxygen to survive. To address this, perforated plastic films are often employed in the production of molded MBCs. These films allow for the exchange of gases, balancing the CO2 levels necessary for growth with the oxygen needed for the organism's survival. Additionally, the choice of whether the final stages of growth occur inside or outside the mold, as well as the presence of texture on the mold walls, can influence the resulting surface finish of the material. It's worth noting that achieving consistent and uniform surface development, including the formation of a soft skin upon contact with the mold walls, can be facilitated by removing the artifact from the matrix and allowing it to continue growing for a few additional days. During this last growth phase, maintaining the appropriate levels and balance between carbon dioxide saturation and oxygen is crucial.

(5-6) Deactivation and use: Once the material has reached the desired level of development, deactivating the organism becomes necessary. This deactivation can be achieved by subjecting the composite to conditions of humidity or temperature that are inhospitable to the organism. Essentially, this can involve either drying and/or heating the artifact. It's important to distinguish between the two methods: high temperatures (around 100-120 °C) permanently halt mycelium growth by killing it, while drying effectively *hibernates* the organism. In the case of drying, the organism's growth could potentially resume if environmental conditions (temperature and humidity) are returned to favorable levels. Furthermore, deactivation through temperature also serves to render the organism non-toxic, should that be a concern.

^ Img.49
Two different artifacts merging through the development of the filamentous network and the superficial aerial hyphae. The anastomosis property allows the mycelium to fuse separate hyphae together and, in the case of two distinct objects, to bind them creating a single matrix with a process know as bio-welding. Material sample from Bio Ex-Machina project by Officina Corpuscoli, 2019.

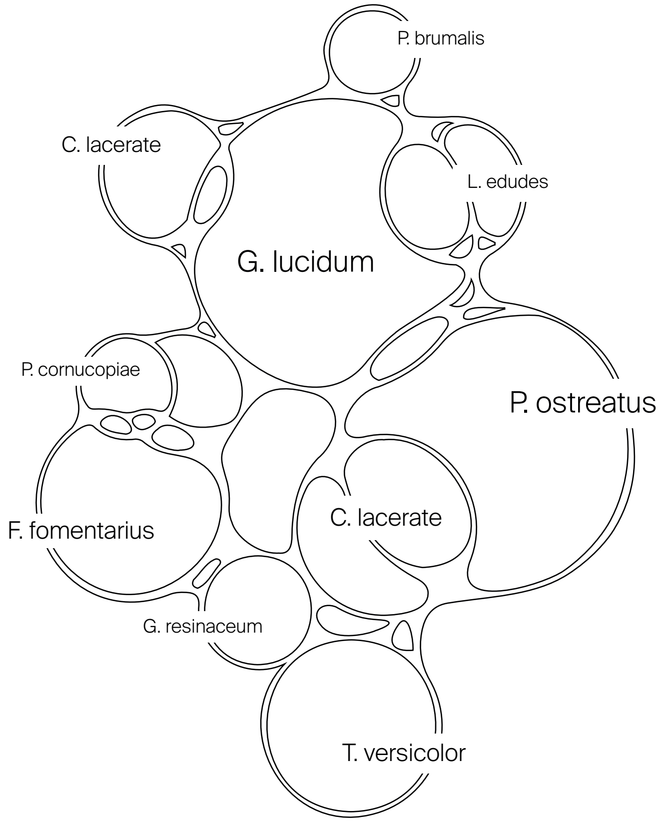
^ Img.50
Growth of the organism and formation of of a thick outer mycelial skin layer, Kineco.bio.

Img.51, 52, 53, 54
MBCs in-mold growth process and formation of the matrix through the substrate's particles. Extracting the artifact to from the mould promotes and enhances superficial growth and develpoment of a thick outer skin. Details of sound absorbing panels growth by Mogu.

TUNING MBCS PROPERTIES 3.3

RELEVANT FUNGAL STRAINS

Img.55
Most frequently mentioned fungal strains in the scientific literature related to the cultivation of MBCs. Grapich redesign of the scheme in Maciej Sydor et al., 2022; Ali Ghazvinian and Benay Gürsoy, 2022.



3.3.1

Fungal strain

As previously discussed, designers have a range of Biofabrication strategies at their disposal to tailor the morphological and mechano-physical characteristics of MBCs. In this research, we categorize these strategies into three main groups, each defined by the variable on which the designer's actions are focused: the choice of fungal strain, the characteristics of the substrate, and the fabrication processes employed.

Selecting the right fungal strain represents one of the most intricate and pivotal stages in the production of mycelium-based composites. Different fungal strains exhibit distinct and specific attributes, including hyphal network density, growth rate, network morphology, ease of cultivation, resilience, harmfulness, and the cost of ideal substrates to support their growth (D. Alemu et al., 2022). Furthermore, not all fungal species possess the same lignin-degrading capabilities, which makes strain selection essential when considering the substrate to be used in conjunction. Typically, most fungal species used in composite production fall into two categories: white-rot and brown-rot fungi. White-rot fungi can break down all wood components, including lignin, whereas brown-rot fungi primarily decompose cellulose and hemicellulose, resulting in a brownish appearance (A. Ghazvinian, B. Gürsoy, 2022). An initial classification is based on the *phylum* or taxonomic group to which these fungi belong, indicating their place in the fungal kingdom. Basidiomycetes (basidiomycota) are the most commonly employed fungal strains in the production of composite biomaterials. This choice is due to their high proficiency in degrading lignocellulosic materials and their ability to adhere to substrates during hyphal permeation of the particle's surface.

Additionally, structurally, fungi within this subkingdom possess a noteworthy attribute: the presence of septate hyphae. Septate hyphae, not universally found in all fungal subkingdoms, are characterized by compartmentalized filaments with septa, which are multiple transverse cell walls. These septa contain minute membrane perforations acting as valves, regulating the flow of molecules, cytoplasm, and organelles along the hyphal length. This feature grants the organism exceptional resilience. In cases of injury or damage to individual hyphae, the organism can manipulate these valves to isolate the affected areas, preventing fluid loss from the rest of the filament (Biologydictionary).

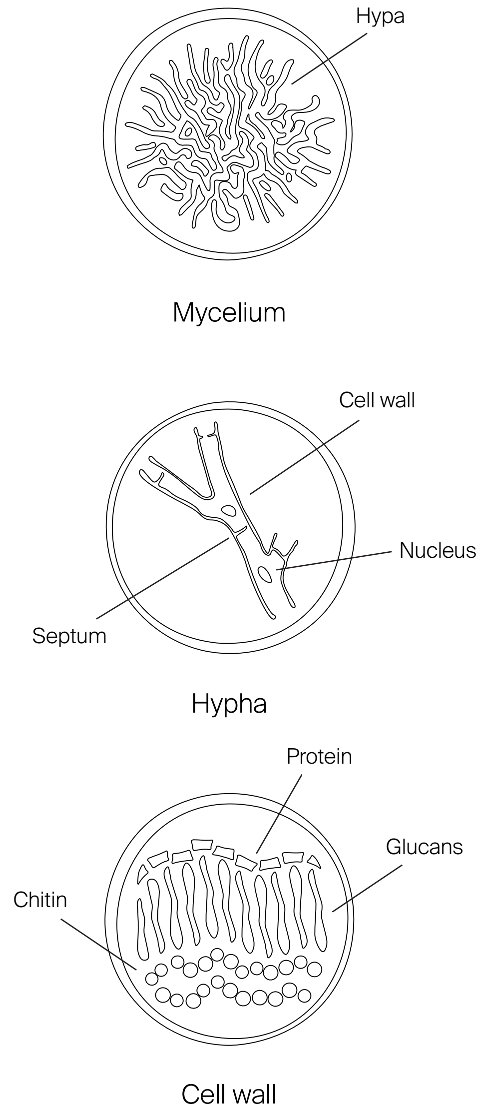
According to Digafe Alemu et al. (2022), the fungal kingdom, particularly the class Agaricomycetes, is home to the two most commonly utilized fungal species for crafting MBCs: Pleurotus ostreatus and Ganoderma lucidum. Pleurotus ostreatus falls under the order Agaricales, family Pleurotaceae, and genus Pleurotus, while Ganoderma lucidum belongs to the order Polyporales, family Polyporaceae, and genus Ganoderma. Fungi within the Agaricales order, such as Pleurotus ostreatus, are known for their ability to produce biomaterials with superior compressive strength and enhanced stiffness. This attribute arises from their excellent colonization capabilities and rapid growth rates when substrates containing lignin, cellulose, hemicellulose, and thick cell walls are employed. Among these, Pleurotus ostreatus, commonly referred to as the *oyster mushroom* or *white oyster*, stands out as the most prevalent species for composite creation. It can swiftly colonize extensive substrate areas within a few days, resulting in a rough and rigid surface. Generally, materials based on P. ostreatus tend to be stiffer compared to those based on G. lucidum and possess a lower elongation at the breaking point (H. Muhammad et al., 2017). However, Ganoderma lucidum, also known as *Reishi*, boasts remarkable growth efficiency, exceptional lignin-digesting capabilities, and the ability to thrive on various natural waste materials. Consequently, it is equally favored for MBC cultivation. Other strains in use include Polyporus brumalis, Lentinula edodes (Shiitake), and Ceriporia lacerata. The latter strain is gaining attention due to its resilience in thriving on unsterilized substrates, a feature that could significantly reduce energy and sterilization costs from an industrial production standpoint (A. Ghazvinian, B. Gürsoy, 2022). Numerous researchers concur that the selection of the fungal species is the primary determinant in achieving high-quality biomaterials. The mycelium's structure in a particular fungal strain directly influences its adherence to the substrate, primarily determined by the chitin content within the hyphae.

Maciej Sydor et al. (2022) have delineated eleven primary characteristics for a sound selection of fungal strains, aimed at bolstering the organism's efficiency in MBC production:

(1) Swift Linear Hyphal Growth: The mycelium's growth rate is a critical factor affecting MBC development time. Opting for a fungal strain with rapid growth

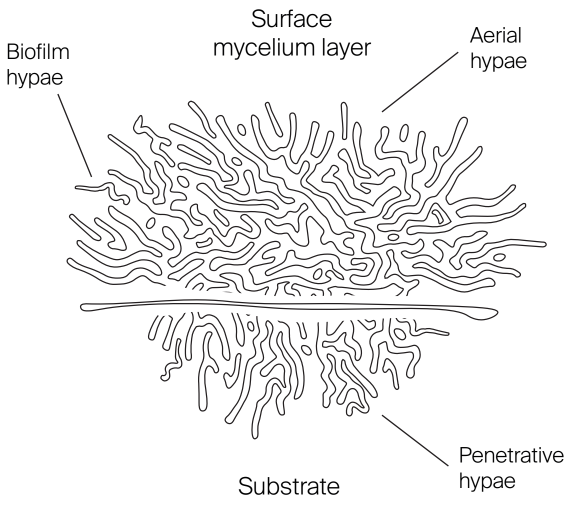
UNTANGLING THE NETWORK

Img.56
Schematic representation of mycelium physiology at different scales. Grapich redesign of the illustrations in Haneef Muhammad et al., 2017.



HYPHAL BONDING

Img.57
Classification of different kind of hyphae during substrate colonization, gaining deep access through rays and branching through fibers. Grapich design from the data in Wenjing Sun et al, 2020.



facilitates the swift acquisition of a usable culture and ensures that MBCs don't suffer excessive substrate degradation due to prolonged organism colonization.

(2) High Virulence: The mycelium should outcompete other microorganisms in substrate colonization, guaranteeing the formation of a composite predominantly colonized by a single organism with uniform physical properties.

(3) Hyphal Structure: Different fungal strains exhibit distinct hyphal structures, potentially including three types of hyphae: generative, skeletal, and binding. Generative hyphae can form reproductive structures and are characterized by thin walls (with occasional slight thickening) and numerous septa. Skeletal hyphae exist in two primary forms. The most common type is thick-walled and considerably longer than generative hyphae, with fewer septa. In contrast, fusiform skeletal hyphae are swollen in the center and often quite broad, giving them a spindle-like appearance. Binding hyphae, characterized by their thick walls and frequent branching, often resemble deer antlers or bare trees due to their numerous tapered branches. Fungi that offer an ideal hyphal structure for biocomposite creation possess at least two of these hyphal types, resulting in a dimitic or trimitic structure, unlike those with a monomitic structure composed solely of generative hyphae.

(4) Fungi producing white molds: these fungi degrade lignin in greater quantities than the rate of degradation of cellulose present in cell walls. This results in a matrix with better physical parameters than would be achieved by using brown or gray mold fungi.

(5) High versatility in nutrition: the mycelium used in the production of MBC must be able to decompose a large variety of lignocellulosic-based material, ensuring versatility to the process in the production phase.

(6) High tolerance to a wide range of substrate parameters and environmental conditions: the fungal strain must be as flexible as possible and compatible with different substrates, their PH and internal humidity as well as the general environmental conditions of temperature and humidity.

(7) Fungus ability to respond to ecological factors: it is important to select mushrooms whose behavior can be easily controlled through factors of temperature, light intensity, carbon dioxide concentration, oxygen concentration or other technological factors.

(8) Easy deactivation of the mycelium: the versatility with which the mycelium is deactivated through various methods guarantees less limitations of size and shape of objects made in MBC.

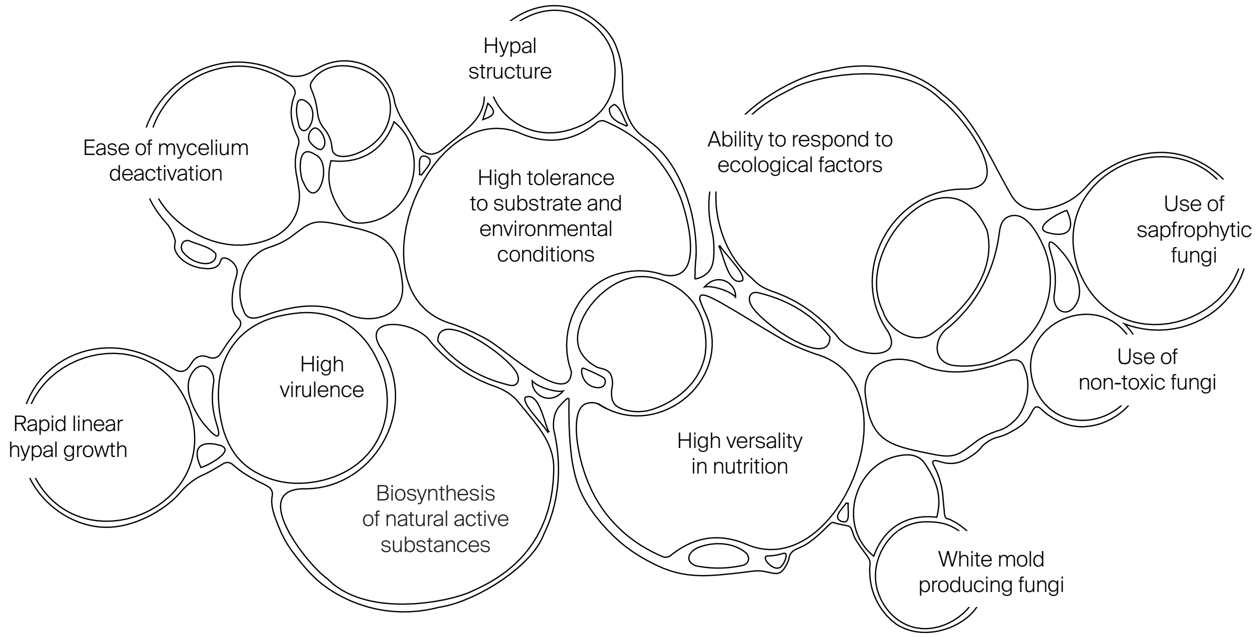
(9) Use of saprophytic fungi: fungal species used for the manufacture of MBC must not be parasitic and must feed only on dead substrates in order not to be dangerous to humans.

(10) Use of non-toxic species: the fungus should not synthesize harmful metabolites, for example *mycotoxins* or *microbial volatile organic compounds* (mVOC).

(11) Promote strains that carry out the biosynthesis of natural active substances: prefer the use of species that synthesize natural active substances, making the process more ecological and creating biocomposites with unique properties.

FUNGAL STRAIN SELECTION

Img.58
The 11 main characteristics that should be taken into account to make proper selection of the fungal strain in order to increase the organism's effectiveness during MBCs fabrication. Grapich redesign of the scheme in Maciej Sydor et al., 2022.



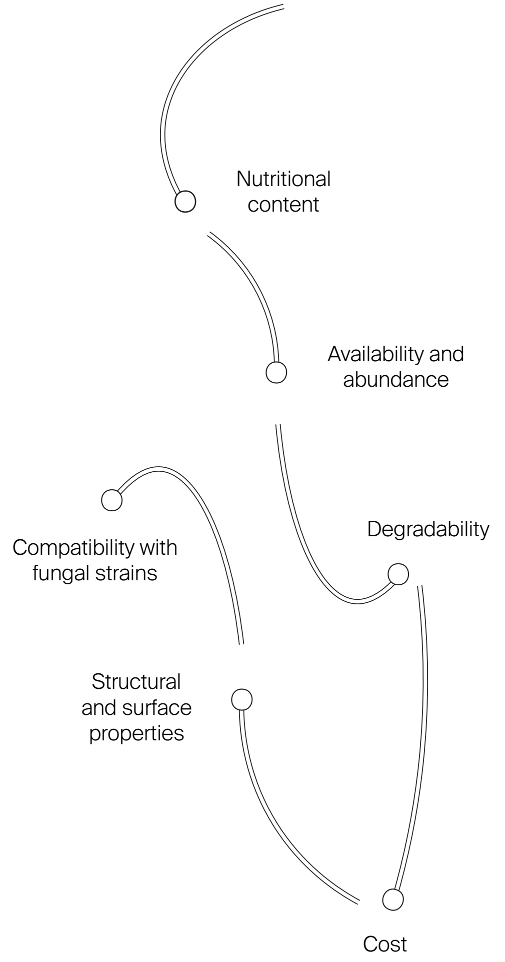
^ Img.59
Actively collaborating with the living material throughout the design and production of the sound absorbing panel, a flexible room divider is formed within a pre-designed mould as the mycelium grows over and bonds with a mixture of plant fibers. Close-up view of the filaments spreading on the substrate's particles, from Jonas Edvard's acoustic wall "MYX Sail / Floor" made in mycelium and plant fibers showcased at "The Mindcraft Project 2023".

3.3.1
Substrate peculiarities

The substrate constitutes the second part of the composite, known as the filler. Since it volumetrically represents almost the entirety of the composite system, the biomass used as the substrate directly influences many properties. In their work, Maciej Sydor et al. (2022) explain how substrates used for MBC production primarily come from three sources: agricultural byproducts, industrial waste, and post-consumer waste. In terms of composition, these substrates can be categorized as "annual plants, softwood, and hardwood. Common loose substrates include various components: wood chips or sawdust, straw (wheat, rice, and others), shredded corn cobs, hemp, recycled paper, nut and seed shells or meal, coffee, nut and seed pulp, coffee grounds, barley grains, and crustacean shells" (p.7). Sydor et al. demonstrate that from the literature, it is evident that the most commonly used substrates are wood, often in the form of sawdust, hemp fibers, wheat straw, cotton fibers, and cellulose (p.8). Wood chips appear more suitable for serving as the filler due to their denser and stiffer nature compared to other waste materials. On the other hand, softer substrates such as hemp, wheat straw, rice straw, and soybean straw are preferred for providing nourishment to the mycelium. As mentioned earlier, the strategy often adopted to ensure optimal organism growth is to combine various substrates that act both as a filler and a nutrient. Among the most commonly used industrial waste materials there are agricultural byproducts like flax waste, coconut fibers, sugarcane bagasse, molasses, various fruit peels, and others (A. Ghazvinian, B. Gürsoy, 2022).

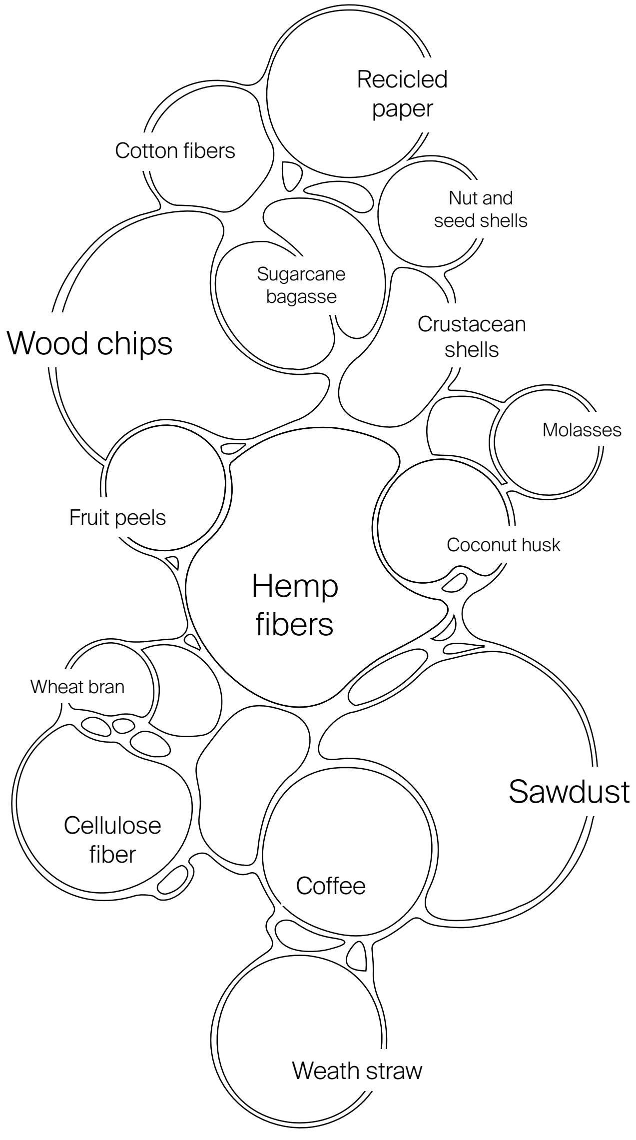
In general, an ideal substrate contains sufficient nitrogen and carbohydrates for rapid fungal mycelium growth. Glucose, in particular, is the primary source of nourishment for fungi, as mycelium breaks down cellulose into glucose molecules for sustenance. Plant-based substrates with high cellulose content confer high mycelium growth rates. Overall, mycelium growth can be promoted by modifying and improving the nutritional content of the substrate. To achieve this, supplements such as wheat bran, rice bran, or agricultural straw can be added. Numerous studies have observed that the growth of the mycelial network appears to be favored by the addition of supplements that also provide increased resistance to compression for MBC. When selecting a substrate, it's essential to consider the following factors: (1) nutritional content, (2) avail-

V Img.60
Six main factors to be taken into account when selecting a substrate in the MBCs manufacturing process. Grapich design of the data in Digafe Alemu et al., 2022.



WIDELY USED SUBSTRATES

Img.61
Most frequently mentioned bulk substrates in the scientific literature related to the cultivation of MBCs. Grapich redesign of the scheme in Maciej Sydor et al., 2022; Ali Ghazvinian and Benay Gürsoy, 2022.



ability and abundance, (3) degradability, (4) cost, (5) structural and surface properties, and (6) compatibility with fungi strains (D. Alemu et al., 2022). The most effective parameters for assessing the efficiency of each substrate-fungus strain pair are the loss of organic matter during the process and fungal growth, which can be measured through empirical measurements of mycelium density and thickness. These parameters are indeed interconnected and dependent on each other. The substrate's mass loss can be explained by the degradation that occurs due to colonization by the organism, during which it progressively consumes the substrate, filling the volumetric voids with the growth of the mycelial matrix. Generally, during substrate colonization, other phenomena related to mycelium growth occur: a slowing down of the substrate's ability to disperse water as moisture because pore size decreases and water retention through capillary action increases (W. Sun et al., 2022), an increase in nitrogen concentration, and a decrease in substrate pH (N. Atias et al., 2017).

The choice of substrate used in the process significantly influences the morphological and mechanical properties of MBCs. According to the research conducted by Haneef Muhammad et al. (2017), it can be asserted that MBCs tend to exhibit greater stiffness when the substrate used as the organism's nutrient is challenging to digest. Through their experiments, which involved comparing different types of mycelium composites produced with cellulose-based and potato dextrose-based substrates, they arrived at intriguing findings. In cases where fibrous materials are used, MBCs display increased mechanical stiffness and a higher Young's modulus, aligning with enhanced compressive strength. This can be attributed to the fact that cellulose is more resistant to hydrolysis than dextrose and poses a greater mechanical challenge for mycelium hyphae penetration. Consequently, mycelium synthesizes more chitin to degrade the substrate, leading to higher composite density. This increased density, driven by chitin, directly influences the stiffness of the composite, as chitin plays a pivotal role in the strength of the hyphal walls. Conversely, MBCs derived from dextrose-based substrates contain less chitin but more protein and lipids, rendering them less rigid and more ductile. However, the reduced chitin content diminishes the water-repellent characteristics of the composite due to inadequate filling of voids within the substrate volume by the mycelial matrix. Notably, composites originating from cellulosic substrates exhibit a thicker and tougher mycelial outer layer compared to those produced from dextrose-based substrates.Another critical factor influencing the mechanical properties of MBCs, apart from substrate nature, is the particle size used. Ali Ghazvinian and Benay Gürsoy (2022) argue that substrate size and processing method have a more significant impact on the physicochemical and mechanical behavior of MBCs than the substrate type. Wenjing Sun et al. (2022) observe that in MBCs, the response to deformation varies depending on the intensity of the applied force. For small stresses, the matrix controls the composite's behavior, while as compression increases, the substrate particles become the primary contributors to the response. Consequently, the choice of substrate particle size becomes crucial in conscious composite design, as under certain loads, the substrate governs the stress response. Eugene Soh et al. (2020) highlight that when using substrate particles smaller than 1 mm, mycelium exhibits increased and faster growth. Specifically, among material sizes of 1mm, 500 μm, and 200 μm, the latter shows the most significant increase in Young's modulus. This phenomenon arises from mycelium's greater ability to colonize smaller substrate particles rapidly, resulting in higher matrix density and greater mechanical strength. However, very small substrate sizes pose the risk of rapid consumption by mycelium, potentially leading to a composite with low density and inadequate strength if the colonization process is not halted at the appropriate time. Conversely, using dusty substrates may hinder air supply to the organism, hampering its growth. Therefore, when designing the dispersed component of mycelium-based composites, a careful balance must be struck among substrate nature, size, and the timing of organism growth.

Img.62
The choiche of the substrate can significantly affect the growth and development of the mycelium. In general, the substrate's composition and the particle size impacts the surface area available for colonization by the organism and can influence the overall colonization rate and efficiency. The optimal particle size can vary depending on the type of mushroom being cultivated and the specific requirements of the project's goal. Experimentation and observation can help determine the ideal peculiarities to be preferred while selecting the substrate.

^ Img.63
Mycelium tiles samples with different growth developments and substrates, Officina Corpuscoli x Mogu.

3.3.3
Processing methods

The myriad combinations of fungal strains and lignocellulosic substrates involved in the process, along with the range of available aggregate geometries, offer designers a vast design space. As previously mentioned, the cultivation and processing of MBCs directly impact their performance. Crucial factors during the organism's cultivation phase include humidity, temperature, and light/dark conditions. However, these parameters vary depending on the fungal strain involved. From this perspective, fungi can be categorized as neutrophils, mesophiles, and extremophiles. While neutrophil and mesophilic fungi thrive under normal conditions, extremophile fungi require extreme temperatures, humidity, or acidity to grow (A. Ghazvinian, B. Gürsoy, 2022). Apart from these environmental factors, a fundamental variable affecting the quality of the material is time. Time, as a cultivation parameter, directly influences material growth, the window of exposure to contaminants, substrate degradation, and density. Adrien Rigobello et al. (2022) identify three primary design strategies for modifying the mechanical behavior of mycelium-based composites: *densification*, *composition*, and *supplementation*. These approaches differ in their intended effects.

Densification involves hot or cold pressing to increase substrate density and stiffen the composite. This strategy includes creating rigid panels pressed at high temperatures, effectively compacting the mycelium network and reducing water content (H. Muhammad et al., 2017). Ali Ghazvinian and Benay Gürsoy (2022) note that hot pressing yields better mechanical qualities than cold pressing, "shifting the performance of composite materials from foam to wood, increasing homogeneity and rigidity" (p.136).

The *composition* strategy aims to alter MBC behavior by incorporating structural components such as oriented fibers or tissues, glass fibers, fiber fabrics, and nanofibers. It also involves changing the properties of particles, often achieved through size reduction via grinding operations. This approach enables the creation of artifacts within MBCs that not only strengthen the structure but also serve as integral components of the object.

Finally, the *supplementation* strategy involves changing the composite's properties through controlled chemical modification of the substrate or by adding additional nutrients. Both the design of the dispersed phase and post-growth processes significantly influence how MBCs respond to mechanical stress and the material's physical and chemical characteristics. Irrespective of the categorization mentioned earlier, it is clear that design choices and cultivation technologies have a profound impact on composite characteristics. The rapid adoption of digital fabrication technologies and growing interest in biomaterials have led to increased material experimentation with their potential. In this context, technologies like Digital Biofabrication explore novel material approaches to enhance MBC performance. The following chapter will highlight examples of these approaches, each proposing distinct co-planning strategies between designers and organisms.

Img.64, 65
Some examples of the “composition” strategy performed by stiffening MBCs through designing geometries with ribs and corrugations. Material samples from Jonas Edvard’s work “Waste - The Everyday Authentic” and prototypes for “The Mindcraft Project 2023”.

Img.66, 67
Incorporation of structural components such as wooden sticks and oriented tissues into the fungal matrix. Examples of the “composition” strategy employable when designing with MBCs, part of the Mycobosci exploration by Adrien Rigobello.

MYCO CULTURES 3.4

3.4.1 Liquid culture

We've so far explored the six primary steps involved in cultivating a mycelium based composite: (1) fungal strain cultivation, (2) substrate preparation and sterilization, (3) substrate inoculation, (4) molding, (5) deactivation, and (6) transport. To delve deeper into the initial phase of fungal strain cultivation, it's crucial to clarify some aspects, building on the information presented in Section 3.1, *Meeting Mycelium*, regarding the overall structure of the fungal organism.

In summary, mycelium represents the vegetative phase of the organism responsible for nutrient absorption, distinct from spores, which are tiny reproductive cells produced by the fungal fruiting body. It might seem logical to assume that mycelium cultivation for mycelium-based composites (MBCs) starts with these tiny spores. However, in reality, fungal cultivation in mycology follows a different process. Initiating cultivation from mycelium stands out as the more efficient and dependable method for several compelling reasons (A. Ogden, 2023). Firstly, mycelium, being a more advanced stage of spore germination, already possesses a network of hyphae capable of absorbing nutrients and promoting growth. In contrast, spores need to germinate and establish a mycelial network before they can produce fruiting bodies. This spore-to-mycelium transition can be slow and unpredictable, as spores may fail to create a robust mycelium or may not germinate at all. Secondly, using mycelium as the starting point for fungal culture ensures the preservation and propagation of desired genetic characteristics present within the filaments. Mycelium can be easily isolated, and its cultivation in a controlled environment guarantees that the resulting organism will consistently yield fruiting bodies with specific traits in terms of size, shape, color, and flavor. Achieving such uniformity becomes challenging with spores, as their genetic characteristics may vary depending on the environmental conditions in which they proliferate. In essence, while spores can indeed initiate fungal cultures, mycelium emerges as a more prevalent and efficient approach for achieving optimal and consistent growth of the organism.

Mushcultblogspot and Jessica Díaz offer a comprehensive exploration of two distinct mycelium cultivation methods, each with its unique technical and practical aspects: liquid culture and cloning via petri dishes. These methods vary significantly in their approach to reproducing the organism, presenting a range of advantages and disadvantages. In broad terms, liquid culture minimizes exposure to contaminants, as it operates in a controlled environment without direct air contact. Conversely, cloning via petri dishes provides superior contamination control, the option to isolate mycelium for culture restarts, and facilitates cloning, especially with advanced equipment. Both cultivation processes involve multiple steps, essential for reducing contamination risk and nurturing mycelium growth before inoculating the final substrate. The pivotal intermediate step between strain cultivation and ultimate inoculation is the introduction of hydrated and sterilized grain seeds, referred to as "spawn." This step, common to both methods, enables rapid and robust mycelium multiplication due to the high protein content of the seeds. Successful growth hinges on precise environmental conditions. The optimal micro-climate for organism proliferation includes sterile spaces, instruments, and ingredients throughout all stages, a consistent temperature between 25-30°C, a constant humidity level between 60-70%, and the absence of light.

^ Img.68
The spawn, consisting of sterilize hydrated cereals, serves as a primary inoculum for the colonization of a larger substrate. The use of spawn in mushroom cultivation allows for the efficient propagation of the organism and ensures a more controlled and reliable production process.

Liquid culture, as the initial myco-culture technique, involves culturing a fragment of tissue from a fruiting body within a nutrient-rich liquid solution. This solution typically comprises water with a 4% proportion of a nourishing substance, such as honey, maple syrup, malt extract, raw cane sugar, etc. The nutrient solution is meticulously prepared, placed in a container, often a modified jar with two accesses. One access regulates gas exchange and requires a filtering mechanism for incoming air, while the other remains sealed and serves as an entry for a sterile syringe used to manipulate the contents without opening the lid. After preparing and sterilizing the solution within a pressure cooker, tissue is taken from the fungus using a sterile syringe and ethanol. The process involves sterilizing the tissue area with ethanol, incising it with a sterilized syringe needle (preheated with a blowtorch), and depositing the tissue into the jar. If executed correctly, mycelium hyphae will begin to grow and multiply within about seven days, thanks to the nutrients in the solution. Mechanical stirring can expedite filament breakdown and growth. After roughly two weeks, the mycelium will have consumed the nutrients, making the solution more transparent. Small white spheres, composed of dense filament clusters, will have formed at the jar's bottom. The jar is then shaken so that the agglomerates of filaments are broken up and dispersed within the aqueous solution to be taken and injected on the spawn. At this stage, the solution is ready for use in inoculating the cereals. Similar to the liquid culture approach, special jars are prepared, and the grains are sterilized in a pressure cooker to eliminate competing organisms. Liquid culture offers a high mycelium concentration using basic equipment but demands meticulous sterility. Contamination during preparation necessitates restarting the entire process.

3.4.2

Cloning via petri dishes

On the other hand, cloning using petri dishes represents the second technique, involving the cultivation of the organism within these specialized containers. Petri dishes, whether made of plastic or glass, are essentially sterile receptacles with lids. In this method, a nutrient solution is prepared by combining starchy potato boiling water and agar agar, a powdered substance derived from algae processing. The mixture is let to cool until it solidifies into a semi-solid state due to the gelling properties of agar agar. A piece of fungal tissue is then placed inside the petri dish. Over a few days, the fungal tissue initiates hyphal growth, expanding radially within the container in a striking fractal pattern. To propagate the organism, a portion of the filamentous tissue from the original specimen is transferred to another petri dish containing the same nutrient solution.

This simplicity of replication is a primary advantage of this cultivation technique over the liquid culture method. A small amount of a single organism can restart a large-scale culture. Additionally, this approach offers excellent contamination control because localized and confined contamination can be addressed by recovering uncontaminated fungal tissue from a separate area within the dish. This ability allows for culture recovery and preservation of the work accomplished thus far by merely transferring into new petri dishes. However, the method's drawbacks are associated with the equipment needed to maintain sterility. Unlike liquid culture, which operates in a closed environment with no exposure to the outside, petri dish operations involve repeated opening and closing of containers in direct contact with the air. To execute this process correctly, sterilizing instruments used for tissue removal with ethanol is essential, and the work must take place within a sterile environment. Achieving sterility is feasible either in front of a laboratory laminar flow hood equipped with a HEPA filter or by constructing a glove box. Both options enable work under sterile conditions, although the cost of laboratory equipment is significantly higher compared to building a homemade glove box. Nevertheless, both solutions operate on the same principle: they incorporate a filter comprising multiple micro-filtering sheets positioned in front of fans that direct air toward the work surface, ensuring a clean airflow during handling. Both the glove box and laminar flow hood methods facilitate the grafting of a robust mycelium culture capable of colonizing the spawn once inoculated. The colonization time for the spawn is comparable to that of liquid culture and results in a resilient and vigorous culture ready for substrate inoculation. This stage, unlike the previous steps, occurs under semi-sterile conditions. Since the mycelium has developed and gained dominance over other organisms, it can colonize the substrate faster than potential competitors, which are neutralized by the fungus at this stage. Nevertheless, it is prudent to work under as sterile conditions as possible or, at the very least, exercise caution during operations. Substrate inoculation involves layering the inoculated spawn with sterilized or pasteurized substrate, typically with an inoculum percentage ranging from 10-15%. After approximately one week, the mixture becomes colonized by mycelium and is ready for use.

Img.69, 70
In the context of mycelium-based composites, the use of liquid culture and petri dishes facilitates the controlled and efficient growth of mycelium, ensuring the purity, uniformity, and viability of cultures, leading to improved yields and consistent quality in MBCs production.

Alemu, D., Tafesse, M., & Mondai, A. K. (2022). Mycelium-based composite: The future sustainable biomaterial. *International journal of biomaterials*, 2022.

Attias, N., Danai, O., Ezov, N., Tarazi, E., & Grobman, Y. J. (2017). Developing novel applications of mycelium based bio-composite materials for design and architecture. *Proceedings of building with biobased materials: best practice and performance specification*, 1(10).

Biologydictionary [Online]. Available at: https://biologydictionary.net/septate-vs-non-septate-hyphae/ (Accessed: 16 April 2023).

Buchanan, P. (2007). Fungi - What are fungi?. *Te Ara - the Encyclopedia of New Zealand*, 24 September [Online]. Available at: http://www.TeAra.govt.nz/en/interactive/11546/fungal-fruiting-body (Accessed 19 September 2023).

Casselman, A. (2007). Strange but true: the largest organism on earth is a fungus. *Scientific American*, 4. Available at: https://www.scientificamerican.com/article/strange-but-true-largest-organism-is-fungus/ (Accessed: 27 March 2023).

Ecovative [Online]. Available at: https://www.ecovative.com/ (Accessed: 22 February 2023).

Fairs, M. (2021). Mycelium is "part of the solution" to carbon-negative buildings. *Dezeen*. 25 June [Online]. Available at: https://www.dezeen.com/2021/06/25/carbon-negative-buildings-mycelium-insulation-fire-proofing/ (Accessed: 1 April 2023).

Gabbatis, J. (2020). Can the wood-wide web really help trees talk to each other? *Science Focus*. 15 May [Online]. Available at: https://www.sciencefocus.com/nature/mycorrhizal-networks-wood-wide-web (Accessed 16 March 2023).

Ghazvinian, A., & Gursoy, B. (2022). Challenges and advantages of building with mycelium-based composites: a review of growth factors that affect the material properties. *Fungal Biopolymers and Biocomposites: Prospects and Avenues*, 131-145.

Haneef, M., Ceseracciu, L., Canale, C., Bayer, I. S., Heredia-Guerrero, J. A., &Athanassiou, A. (2017). Advanced materials from fungal mycelium: fabrication and tuning of physical properties. *Scientific reports*, 7(1), 41292.

International Online Medical Council [Online]. Available at: https://www.iomcworld.org/medical-journals/mycelial-mass-51815.html (Accessed: 23 March 2023).

Islam, M. R., Tudryn, G., Bucinell, R., Schadler, L., & Picu, R. C. (2017). Morphology and mechanics of fungal mycelium. *Scientific reports*, 7(1), 13070.

Johnston, E., Brewer, G. (2023). Mycelium: Exploring the hidden dimension of fungi. *Royal Botanical Gardens Kew.* 11 March [Online]. Available at: https://www.kew.org/read-and-watch/fungi-hidden-dimension (Accessed 15 March 2023).

Micropia - Science museum Amsterdam "Mycelium - Network of fungal threads". *Microbiology from A to Z*, [Online]. Available at: https://www.micropia.nl/en/discover/microbiology/mycelium/ (Accessed 20 September 2023).

Mogu [Online]. Available at: https://mogu.bio/ (Accessed: 22 February 2023).

MycologyWiki [Online]. Available at: https://mycology.fandom.com/wiki/Mycology_Wiki (Accessed: 16 April 2023).

O'Brien, H. E., Parrent, J. L., Jackson, J. A., Moncalvo, J. M., & Vilgalys, R. (2005). Fungal community analysis by large-scale sequencing of environmental samples. *Applied and environmental microbiology*, 71(9), 5544-5550.

Ogden, A. (2023). The difference between mushroom spores and mycelium. *Mushrooms Growing Guides*, 4 April [Online], Available at: https://www.gourmetmushrooms.eo.uk/the-difference-between-mushroom-spores-and-mycelium/ (Accessed: 1 June 2023).

Pandey, P. (2020). Fungi: distribution, morphology, reproduction, classification. *We Are Marketing*. 10 July [Online]. Available at: https://microbiologynotes.org/fungi-distribution-morphology-reproduction-classification/ (Accessed: 29 April 2023).

Pizzulo, M. (2023). Funghi e Salute. Biogem, 23 February [Online]. Available at: https://www.biogem.it/index.php/it/la-ricerca-a-tavola/570-funghi-e-salute (Accessed 20 October 2023)

Rigobello, A., Colmo, C., & Ayres, P. (2022). Effect of composition strategies on mycelium-based composites flexural behaviour. *Biomimetics*, 7(2), 53.

Soh, E., Chew, Z. Y., Saeidi, N., Javadian, A., Hebel, D., & Le Ferrand, H. (2020). Development of an extrudable paste to build mycelium-bound composites. *Materials & Design*, 195, 109058.

Sun, W., Tajvidi, M., Howell, C., & Hunt, C. G. (2020). Functionality of surface mycelium interfaces in wood bonding. *ACS Applied Materials & Interfaces*, 12(51), 57431-57440.

Sydor, M., Bonenberg, A., Doczekalska, B., & Cofta, G. (2021). Mycelium-based composites in art, architecture, and interior design: a review. *Polymers*, 14(1), 145.

Sydor, M., Cotta, G., Doczekalska, B., & Bonenberg, A. (2022). Fungi in mycelium-based composites: usage and recommendations. *Materials*, 15(18), 6283.

Sun, W., Tajvidi, M., Howell, C., & Hunt, C. G. (2022). Insight into mycelium-lignocellulosic bio-composites: Essential factors and properties. *Composites Part A: Applied Science and Manufacturing*, 161, 107125.

Treccani [online]. Available at: https://www.treccani.it/vocabolario/fungo/ (Accessed: 20 March 2023).

CHAPTER 4

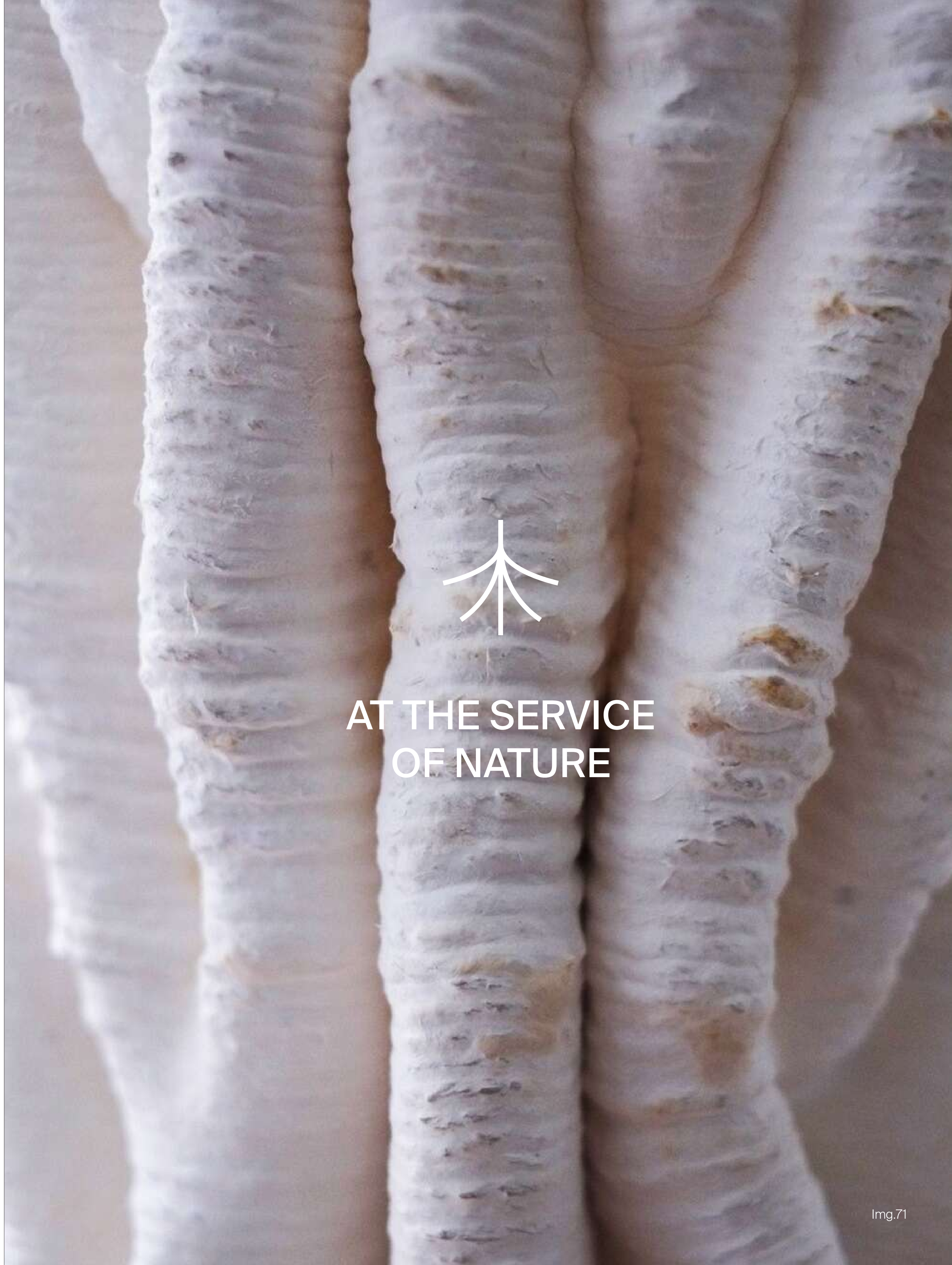
4.1 MOULDING WITH MBCS

3D PRINTING 4.2 WITH MYCELIUM

4.3 INJECTING LIQUID CULTURES

IN-DEPTH 4.4 ANALYSIS

... The opportunity on the designer's side to actively participate in the growth phase of the material generates broad potentials in which he is able to design and adjust its qualities, making not only the material, but the entire process "alive, active and adaptive" ... ... the strategies by which the growth of the material was guided, the limitations and obstacles encountered during their realization, how design was put at the service of nature, and how nature in turn was at the service of design ...



Img.71

Img.72
Close-up view of the mushroom fruiting bodies taking over the surface of the MYX lamp designed by Jonas Edvard in 2013. This project was one of the first creation in development of the Mycelium Textile project as a part of his final graduation project at the Royal Academy of Fine Arts, School of Design in Copenhagen Denmark, paving the way for the design world to discover the potential of MBCs.

In the third chapter, we delved into the intricate world of mycelium, providing a comprehensive analysis of this organism from various angles including taxonomy, chemistry, physics, and behavior. We also investigated the potential of harnessing this organism for the development of composite materials known as MBCs. These materials exhibit exceptional properties, making them both pioneering and sustainable alternatives poised to replace conventional materials in various applications in the foreseeable future. The involvement of designers in the growth phase of these materials presents a significant opportunity, enabling them to actively shape and customize the material's qualities. This not only breathes life into the material itself but also renders the entire process *alive, active and adaptive*. Within the scope of manipulating the properties of MBCs, the primary influencing factors revolve around the specific fungal strain, the substrate used, and the employed production processes. This chapter delves into a detailed examination of several case studies, emphasizing the significance of the cultivation approach, the utilized technologies, and the designer's role throughout the entire production process. These case studies underscore the remarkable versatility achievable in the creation of MBCs. Some of the projects examined showcase a collaborative relationship between the designer and the organism, aligning closely with the principles of Growing Design, while others fully capitalize on the potential of Digital Biofabrication. Particular emphasis is placed on the practices of molding with MBCs, 3D printing with mycelium, and the injection of liquid cultures.

Of each of these artifacts, the strategies by which the material growth was guided, the limitations and obstacles encountered during their realization, how design was put at the service of nature, and how nature in turn was at the service of design will be highlighted.

MOULDING WITH MBCS 4.1

4.1.1

Crafts Mycelium Furniture by Philip Ross

The primary case study at hand revolves around the series of works developed by Philip Ross, an American artist, professor, and entrepreneur, since the early 2000s. Ross has dedicated his career to exploring the diverse applications of mycelium, demonstrating a pioneering approach in utilizing fungi as an artistic medium, ranging from furniture to architectural elements and sculptures. His notable achievements encompass a series of seats crafted from MBCs and several small-to-medium-scale architectural projects. The seats under examination emerged from an exploration conducted during the early stages of the relatively unexplored field of MBCs. Ross's journey commenced even before the materialization of this collection, a time when the internet was not a repository of abundant information and the community of experts lacked the present-day inclination towards knowledge sharing (P. Ross in A. Scott, 2012). Presently serving as the co-founder and CTO of Mycoworks, a company specializing in cultivating mycelium biomaterials for commercial use in the fashion industry, Ross' work serves as a significant milestone in this domain. His approach exemplifies the *composition* strategy outlined in the preceding chapter, particularly emphasizing the use of inserts to reinforce structural integrity.

The collection comprises a series of seats crafted from mycelium, utilizing sawdust as a substrate, with salvaged wooden legs from other furniture serving as integral structural components. Manufactured over a span of eight weeks at *The Workshop*, an industrial hub in San Francisco catering to independent makers and designers on two-month residencies (G. Thomas, 2012), Ross initiated the production of seat tops and backs by infusing sawdust with Ganoderma lucidum tissue, allowing the amalgamation to foster within molds of the desired shape. The expedited growth rate of this fungal strain facilitated the creation of compact and durable volumes, ensuring a comfortable user experience. Ross' confidence in the material's robustness was exemplified when he tested its shock-absorbing capabilities by firing a .38-caliber bullet at point-blank range at a brick composed of the same MBC material as the seats, with the bullet penetrating merely 5 inches. Beyond its innovative nature over a decade ago, Ross' work is distinguished by the amalgamation of the composite material, intricate geometries, and the incorporation of supplementary components that bolster structural support. The designs of the seat legs manifested in close symbiosis with the composite's geometries, forging various joint connections. Some featured interlocking joints, while others were fastened using bolts or adhesives, leveraging surface adhesion. This approach facilitated the direct cultivation of the composite material in conjunction with the inserts, effectively guiding the mycelium's growth. Leveraging the geometries of these inserts facilitated the organic growth process, resulting in artifacts without mechanical joints, but instead, envisaging these elements as an integral part of the growth design process. Notably, an external component, when submerged within the mycelium-inoculated substrate, swiftly became enmeshed within the chitinous matrix as the organism commenced its growth and substrate digestion. Alternatively, if mycelium growth occurred in contact with the inserts without encapsulation, deactivating the mycelium allowed for subsequent assembly of the components. The potential to create mechanical joints directly on the MBC components further underscored the composite's exceptional attributes, enabling post-production processing and facilitating connections without solely relying on the organism's bio-welding properties.

Img.73, 74
The Benign Yamanaka stool, on display at The Workshop Residence in San Francisco. On the right image Pamela Pascual, works on her vessel in a grow-your-own furniture class at The Workshop Residence in San Francisco, October 13, 2012.

^^ Img.75, 76
Mycelium arc and sculptures built by using bricks made of MBC, Philip Ross. By using mycelium bricks, the artist has created artifacts that showcase both the structural capabilities and the aesthetic appeal of this organic material. Through his work, Philip Ross encourages a reevaluation of traditional construction methods and promotes the integration of innovative and environmentally friendly solutions into contemporary design and sculpture.

^ Img.77
^ Mycelium Sausages is a technique in which the inoculated substrate is pushed into a cotton bandage and freely woven into a shape that will solidify into a robust structure over few weeks thanks to the growth of the organism. The process can be thought of as something between traditional rattan weaving and manual 3D printing, as it allows one to form a diverse range of shapes using a long tube of MBCs. The technique was developed by Caracara Collective in 2017 to explore new ways of fabricating mycelium objects without the need for moulds.

4.1.2

Mycelium Sausages by Caracara Collective

The inventive method known as Mycelium Sausages was conceptualized by the Caracara Collective, a design studio based in Helsinki, Finland, renowned for their utilization of biowaste in creating collections and installations. This technique, as the name implies, involves stuffing inoculated substrate into a cotton bandage, intricately woven into the desired shape, and left to be colonized by the organism. Within a span of two to three weeks, this process yields robust, sausage-like structures capable of assuming various braided configurations through the use of one or more continuous mycelium *sausages*. The technique, pioneered by studio owners Aleksi Puustinen and Aleksi Vesaluoma, is described as a fusion between traditional rattan fiber weaving and manual 3D printing. The Mycelium Sausages technique initially emerged as a project at Brunel University in London in 2016, subsequently refined and unveiled at the London Festival of Architecture in June 2017. Its genesis lay in the quest to develop novel methods for fabricating MBCs without relying on growth molds, enabling the cultivation of site-specific, free-form structures independent of the constraints of modular final forms.

What sets this technique apart from other composite growing strategies that typically necessitate mold usage is the employment of a soft, non-invasive cotton mesh as the mold substitute. This mesh not only helps maintain the shape but also provides the structure with the necessary flexibility for bending, weaving, and knotting. Temporary support structures or tensile structures are employed during the growth phase, subsequently removed once the cultivation process concludes. The application of the Mycelium Sausages technique spans an array of artifacts, including furniture pieces, baskets, and architectural structures. The structural integrity of these creations hinges upon the exploitation of connections and interweaving within the continuous *sausage*.

Of particular significance is the phenomenon of bio-welding, which ensures the structural rigidity of these objects. This bio-welding process enables the fusion of different components, solidifying layers during the growth process. Without this unique capability of the organism to fuse intertwined components, the resulting geometry would be a tangled configuration with reduced structural stability, vulnerable to collapse under its own weight. The pavilion crafted by the Caracara Collective exemplifies the symbiotic relationship between the organism and the designer, accentuating the properties of mycelium alongside deliberate and astute design choices. This collaboration signifies an elevated design concept and an ecologically sound alternative to conventional construction methods and materials.

Img.78, 79, 80
On the left page Mycelium Sausages pavilion, 2017, on the right one Mycelium Sausages lamp, stool and basket by Caracara Collective, 2017.

Img.81
MYX Chair by Jonas Edvard, Walden exhibition at Schloss Hollenegg castle, 2022.

4.1.3

MYX by Jonas Edvard

Jonas Edvard, an esteemed Danish designer, has been ardently exploring the possibilities of living materials since 2012. Notably, the *Mycelium Textile Project* (MYX) serves as a pivotal investigation into the diverse properties of MBCs, with an emphasis on their various combinations and adaptations within the sphere of product design. His meticulous research primarily centers on devising design solutions that amplify the material's inherent qualities, meticulously considering both its compositional intricacies and its versatility in terms of form and practical application. The culmination of his research and expertise is vividly demonstrated through an array of meticulously crafted objects, ranging from chairs, stools, and lamps to tiles and the recently showcased acoustic panel *MYX Sail / Floor* at the *The mindcraft project exhibition* in 2023. These pieces bear witness to his profound understanding of the material and a profound reverence for the integral role the organism plays in the collaborative process of artifact creation. Before realizing the complex geometry of objects constructed from MBCs, Jonas Edvard conducted several material studies, experimenting with various substrate compositions and innovative processing methods to corrugate composite sheets. Utilizing strategic folds and ribs, he aimed to ensure structural resilience, even when working with reduced thicknesses.

The MYX Chair and MYX Stool, for instance, are prime examples of Jonas's adept manipulation of the material, demonstrating an intelligent balance between form and function. Employing sheets of hemp fibers intricately folded multiple times, these designs facilitate the organism's growth, cementing the shape and ensuring exceptional rigidity. A significant challenge lay in the intricate design process and the meticulous resolution of force distribution within the structural elements. The stool, characterized by several identical components arranged in a radial pattern, ingeniously disperses the seating load both horizontally through the foldings of the seat top and vertically via the strategically placed vertical ribs. In contrast, the chair comprises fifteen modules that are intricately crafted through internal folding, mirroring the ribbing of corrugated cardboard. The assembly of both artifacts involves carefully aligning individual components and harnessing the inherent bio-welding capabilities of mycelium, thereby ensuring a cohesive and robust final structure.

In his innovative approach, Jonas's *composition* strategy not only enriches the material properties during the structurally oriented substrate phase but is complemented by the technique of *densification*. This method involves carefully compressing the MBC sheets and securing them in place using a sophisticated clamping system, ultimately facilitating the natural bio-welding process of the organism. The result is a sophisticated and resilient creation that stands as a testament to the intersection of art, design, and ecological consciousness.

Img.82, 83, 84, 85
On the left page MYX Stool, 2015, on the right one MYX Chair, 2020, works by Jonas Edvard. These pieces exemplify Edvard's dedication to using natural materials in innovative ways and tuning their properties to meet specific design goals. These furniture pieces, thanks to the strategies involved in their stiffening, represent a harmonious blend of functionality, aesthetics, and sustainability, reflecting Edvard's commitment to creating products that are functional, visually appealing and environmentally conscious.

3D PRINTING WITH MYCELIUM

4.2

4.2.1

Mycelium chair by studio Klarenbeek & Dros

Eric Klarenbeek, a distinguished Dutch designer renowned for his innovative contributions, leads the esteemed studio Klarenbeek and Dros, situated in the vibrant locale of Zaandam, just on the outskirts of Amsterdam. In a significant display of creativity, he unveiled the pioneering Mycelium Chair at the Dutch Design Week in 2013, marking a notable milestone in the convergence of materials derived from living organisms and the precision of digital fabrication (M. Fairs, 2013). This visionary project was cultivated in close collaboration with esteemed scientists from the University of Wageningen, the Netherlands, whose invaluable expertise facilitated the meticulous preparation and nurturing of the intricate biomaterials integral to the chair's creation.

The intricacy of the chair's construction is a testament to Eric's meticulous approach. The external shell, digitally fabricated through 3D printing using PLA, forms the initial framework that serves as a nurturing environment for the thriving organism, filling voids and fortifying the structural integrity. Each component of the furniture is produced separately, with individual 3D printing and subsequent filling with a specially prepared straw paste inoculated with the mycelium. Notably, the deliberate selection of the Pleurotus cornucopiae strain, notable for its distinctive yellowish tinge, serves both an aesthetic purpose and as a vivid demonstration of the organism's proliferation. Following a carefully monitored growth phase spanning 1 to 3 weeks, contingent on various environmental factors, the assembled pieces are delicately joined together through the precise process of bio-welding, allowing for the subsequent removal or retention of the scaffold. The result of this intricate process is a remarkably lightweight yet exceptionally sturdy structure, achieved through the gradual assimilation of the substrate by the mycelium, culminating in a resilient matrix that seamlessly fills voids and adheres firmly to the structure's contours. Continuing his exploration, in 2019, Eric delved even deeper, experimenting with a new iteration of the Mycelium Chair, this time harnessing the unique properties of Ganoderma lucidum. This updated version not only represents a stunning aesthetic evolution but has also earned a distinguished place within the prestigious permanent collection of the esteemed Centre Pompidou in Paris. Significantly, this particular chair was crafted for inclusion in the *La Fabrique du Vivant* exhibition, a testament to its exceptional design and ecological significance within the contemporary art and design landscape. Undoubtedly, the pivotal role of digital fabrication within this process cannot be understated. Beyond enabling the production of intricately complex shapes unattainable through traditional methods, the precision afforded by 3D printing ensures the meticulous accuracy necessary for the successful culmination of the growth process. Acting as an essential scaffold, the 3D printed structure not only guides the material's growth but also offers indispensable structural stability during the critical inoculation phase. Subsequently, it is the ability of the organism unique to bestow rigidity upon the final structure that elevates the chair's design, exemplifying the symbiotic relationship underscored in earlier chapters. This intricate and symbiotic collaboration between biologically nurtured materials and the precision of digital design, facilitated and mediated by the designer's vision, symbolizes a progressive step towards achieving paramount design excellence and ecological harmony.

Img.86, 87
The first prototype of the Mycelium chair by Studio Klarenbeek and Dros, 2013. A thin layer of bioplastic was used to print the modules of the chair structure to serve as a guide element for fungal growth. The inoculated substrate was mixed and printed simultaneously with the outer walls as a filler, then the organism was deactivated to prevent further growth.

^ Img.88
Second prototype of the Mycelium chair designed by Studio Klarenbeek and Dros crafted using Ganoderma Lucidum strain, acquired in 2018 by the Centre Pompidou in Paris, France, and part of its permanent collection.

4.2.2

Hyper Articulated Myco Morphs by Jessica Dias

The project *Hyper Articulated Myco-Morphs* emerged from the visionary efforts of Jessica Dias in 2017 at the Institute for Advanced Architecture of Catalonia in Barcelona. Delving deep into the intricacies of designing artifacts within the realm of MBC, the project consciously directed the design phase towards fostering both aesthetic complexity and functionality conducive to the organism's growth. The overarching aim of this research was to foster the creation of novel formal languages that seamlessly align with the intricate dynamics of the involved organism, serving to stimulate its growth while guiding and preempting its behavior. At the crux of this undertaking lies the development of a prototype table, fabricated through the 3D printing of a PLA frame that transiently serves as a scaffold for mycelium cultivation.

Under Jessica's leadership, the design phase was complemented by a rigorous experimental process, commencing with cloning via Petri dishes and agar agar. This journey of exploration traversed various growth factors and substrate optimization techniques, culminating in the fabrication of the same composite material deployed within the project. Fieldwork proved instrumental, offering valuable insights into the organism's behavior and facilitating the derivation of behavioral patterns to be seamlessly integrated within the design phase. Consequently, the morphology of the final prototype was intricately informed by the wealth of information gleaned during the meticulous investigation into growth conditions, precise recipe proportions, and the intricate textures of the substrate. The geometric configurations prototyped and meticulously delineated by the designer bore a striking resemblance to the intricate lamellae found beneath the cap of a mushroom. However, in this context, these forms served the purpose of generating volumes conducive to the optimal environmental conditions necessary for mycelium proliferation. A design integrating pockets and shaded areas, adept at retaining moisture more efficiently, notably facilitated an accelerated and more effective development of the organism. Leveraging the capabilities of Grasshopper, the modeling process of these intricate geometries was conducted parametrically, facilitating seamless adjustments and ultimately contributing to the attainment of an organic aesthetic. The strategic introduction of these parameters facilitated a more expansive upper part of the table, resulting in the thinning of lamellar thickness and thereby promoting heightened mycelium growth within this domain. Thus, this design methodology underscored the crucial symbiosis between the designer's visionary goals and the indispensable conditions requisite for the organism's flourishing.

Contemplating a personal meeting in February 2023, I had the honor of engaging in a profound conversation with Jessica herself, conveying my sincere appreciation for her invaluable insights and kindness. Our dialogue not only delved into the intricacies of her project and the meticulous strategies deployed during its execution but also illuminated her ongoing research initiatives channeled through her esteemed studio, Biobabes. This pioneering studio remains deeply committed to the continual exploration of a diverse array of biomaterials, building upon the foundational groundwork initiated by this very project. Moreover, our exchange served as a pivotal compass guiding my future design trajectory, offering invaluable guidance and constructive feedback pertaining to the optimal strategies to be embraced throughout the upcoming phase of material experimentation.

^ Img.89, 90, 91
3D printed shape investigation from the Hyper Articulated Myco Morphs project by Jessica Dias. The geometries have been computationally designed on Grasshopper to simulate the complexity of organic patterns of growth and create inlets and cavities to promote the development of the organism. The fungus, by growing between the hollows parts creates a dense matrix which acts as a solid reinforcement.

Img.92
Pulp Faction is a transdisciplinary project conducted by Ana Goidea and D.Andreén that developed a method for 3d printing mycelium composite materials for architectural use. The project employs the transformative power of mycelium to propose self-supporting, hydrophobic, good thermal and acoustic insulators structural elements. The process has been demonstrated through a 2 meters high column, named Protomycokion.

4.2.3

Pulp Faction by A.Goieda and D.Andreén

The *Pulp Faction* project, initiated in 2020 at Lund University in Sweden by Ana Goidea and David Andreén, represents a significant leap in the realm of architectural material development. Focused on harnessing the inherent structural reinforcement properties of the mycelial network, the project is centered around the creation of a 3D printable mycelium-based composite material, specifically tailored for application within the domain of architecture. Their notable endeavor involves the construction of a column, named Protomicokion, crafted from multiple modules, each intricately formed through the extrusion of a specialized cellulosic-based pulp, poised to be colonized by the dynamic organism. Central to the project's underlying philosophy is a critical examination of the prevailing contradictions prevalent within the contemporary construction industry, shedding light on the staggering energy consumption, CO2 emissions, and prolific waste generation inherent in traditional construction practices. In response, Pulp Faction proposes a revolutionary shift in the construction paradigm, advocating for a sustainable trajectory that emphasizes the growth of materials over conventional extraction practices. What sets this initiative apart is not only its innovative utilization of cutting-edge digital fabrication technology but also the intricate design strategy underpinning the development of digital models. Meticulously calibrated to optimize the column's structural integrity and the organism's growth potential, the computational modeling tools prioritize the precise calculation of the optimal ratio of surface area to volume. The resulting intricate geometries, carefully derived from this meticulous approach, serve a dual function. Firstly, they facilitate enhanced oxygenation, thus fostering optimal mycelium growth by maximizing the organism's exposure to gaseous exchange. Secondly, these intricate formations contribute significantly to the structural robustness of the column, intricately interweaving folds and creases that strengthen the overall integrity of the structure. Notably, the calculated folds and creases play a crucial role in mitigating potential weaknesses within the structure, reducing the need for extensive thermal stabilization treatments post-deactivation of the fungus.

However, one notable challenge emerged during the assembly phase - the project refrained from fully capitalizing on the potential of the organism's bio-welding property. The great size of the column rendered heat-based deactivation unviable without access to specialized and sizeable equipment. Consequently, this limitation underscored the necessity to explore alternative solutions for connecting the modules, highlighting the untapped potential of the organism's unique properties that warrant further exploration and experimentation.

^ Img.93,94
On the left page close-up view of the colonised material surface of the Protomicokion coloumn, on the right one detailed view of the intricate geometry of the modules, designed to improve the stiffness of the structure in order to make it a self-standing architectural element.

INJECTING LIQUID CULTURES

4.3

4.3.1

Bio Scaffolds by BioLab Studio

The visionary project *Bio Scaffolds*, introduced by Natalia Alima at the helm of the BioLab Studio in 2018, represents a groundbreaking fusion of digital fabrication and organic growth processes, reflecting a compelling exploration at the cutting edge of design and technology. At its core, the project unfolds as a series of meticulously crafted sculptures, each of them 3D printed using a specialized filament that ingeniously incorporates sawdust later infused with liquid mycelium cultures by a computer controlled robotic arm.

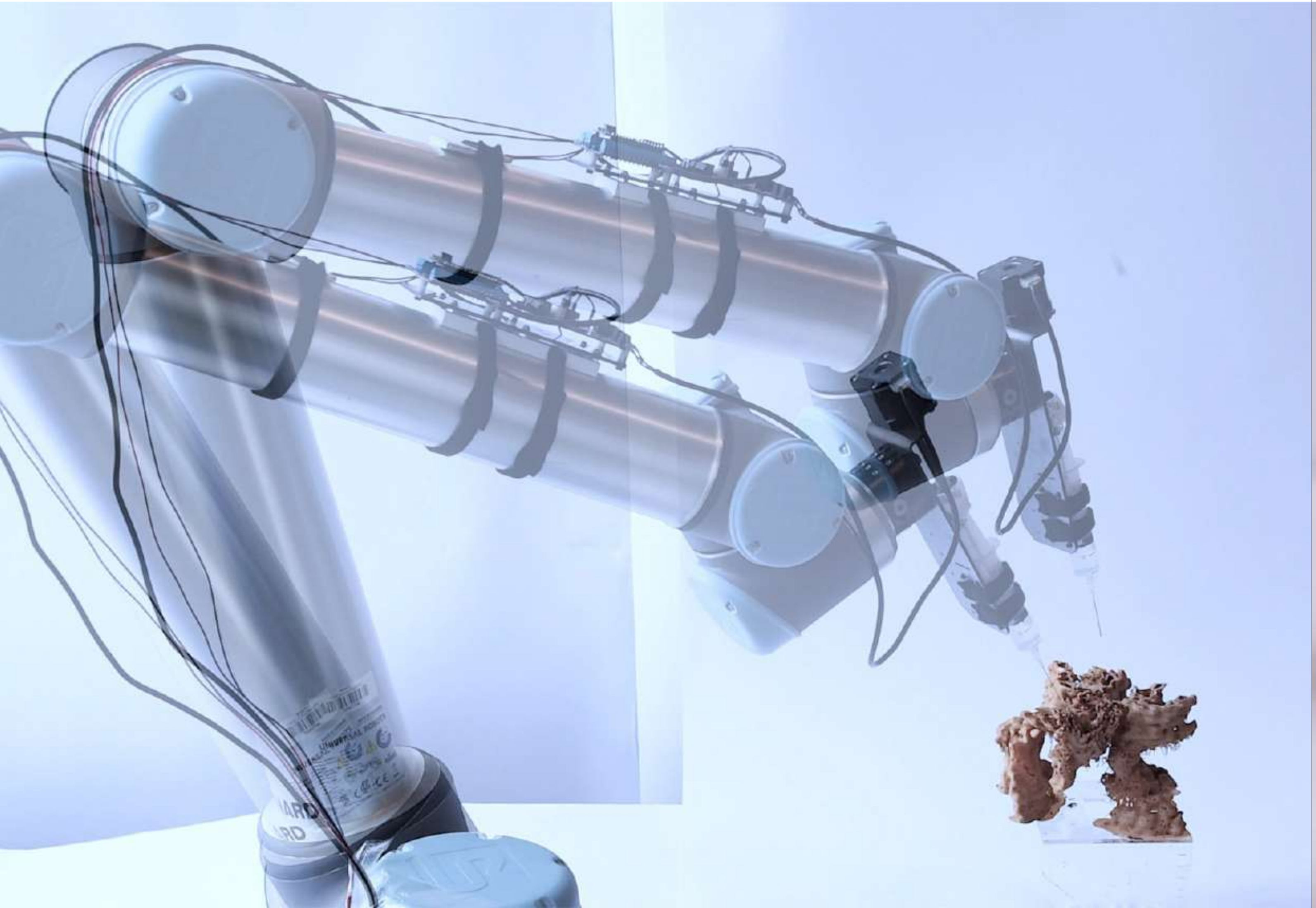
The intricacies of the project unfold through an orchestrated interplay, involving a finely calibrated robotic arm that expertly directs the injection of the mycelium solution directly into the scaffolds, leveraging the material's inherent porosity to facilitate seamless absorption. Notably, the system remains silent awaiting for the organism's vital signs, keenly observing biometric parameters such as shifts in color and moisture levels, prompting corresponding actions orchestrated by the responsive robotic arm. The comprehensive setup boasts a formidable array of cutting-edge components, including the utilization of a Universal Robotics UR10 robot, expertly guided by the capabilities of Grasshopper, alongside an Arduino humidity sensor, a strategic webcam, and a bespoke multi-tool housing a precision-engineered robotic syringe. The driving force behind the project lies in the profound synergy established between the digital components and the organic growth process. Natalia's design process is underpinned by a delicate balance, delicately navigating the intricate relationship between the artificial computational algorithm and the organic algorithm inherent within nature. The resulting artifacts are carefully crafted, harnessing the power of algorithms to intricately generate dynamic geometries replete with micro valleys and intricate pathways, meticulously fostering optimal mycelium infiltration and propagation. This interplay is further enhanced by the conscious integration of 3D printing technology, strategically selecting a sawdust-infused filament that seamlessly promotes material porosity, thereby enhancing the intricate details and complexities of the final output.

This holistic approach engenders a profound and interdependent relationship between the machine and the organism, operating independently in their intent yet remaining intricately interconnected through their actions. Natalia's conceptualization resonates deeply

Img.95
Close-up view of the UR10 robotic arm injecting mycelium liquid culture into the sawdust-based filament scaffold. Operating silently, the system monitors the organism's vital signs, responding to changes in color and moisture levels, Biolab Studio.

with the concept of *swarm intelligence*, drawing inspiration from the decentralized and self-organizing systems observed in the natural world, where collective behaviors emerge without central directives (Hewlett Packard Enetrprise). This captivating symbiotic interplay between digital fabrication, robotic precision, and the dynamic evolution of the organism serves as a testament to the seamless collaboration between human ingenuity and the boundless potential of nature, reshaping the frontiers of modern design exploration.

Img.96, 97, 98
On the left page, the UR10 robotic arm injecting mycelium liquid culture into the sawdust-based filament scaffold. On the right page one of the 3D printed sculptures to be colonized by the organism in the first image, and after colonization in the second, BioLab Studio.



Img.99
Endless Lovers, inspired by the Endless column of Constantin Brancusi, were two different 3D printed artifacts that grew together and merged to become one. Made of reishi mycelium grown on a coffee cups waste materials, Blast Studio. Endless Lovers is part of the permanent collection of the Musée des Arts Décoratifs in Paris, France.

IN-DEPTH ANALYSIS 4.4

4.4.1

Blast Studio conference at IV Crafts NOW., 2023

On the 26th and 27th of January 2023, I had the privilege of attending the fourth edition of the *Crafts NOW. Festival d'artesania y innovaciò* held at the esteemed Disseny Hub Barcelona. Hosted by the Association of FAD Artists and Artisans (A-FAD), this annual event stood as a testament to the Government of Catalonia's concerted efforts to foster a supportive ecosystem for artisans, craftspeople, and makers, thereby facilitating the exploration of innovative ideas within the domain of traditional craftsmanship. Emphasizing the need for a more adaptable crafts framework that could effectively respond to contemporary societal and environmental challenges, the 2023 festival revolved around the theme of *Crafts NOW*, aiming to advocate for a forward-thinking approach that amalgamates traditional craftsmanship with cutting-edge technological advancements. The festival, through a thoughtfully curated series of seven insightful conferences, aimed to address the pressing challenges of the modern crafts landscape, spanning diverse areas such as innovation, community engagement, sustainability, and gender equality. Each lecture and discussion provided a comprehensive perspective on the role of material experimentation and the integration of novel technologies, fostering a compelling narrative for the future trajectory of the crafts sector.

One of the most captivating sessions was a lecture delivered by Blast Studio, a London-based design firm founded in 2018 by the visionary trio of P. Garnousset, M. Detoeuf, and P. de Pingon. Known for their endeavors in harnessing the symbiotic potential of nature and technology, Blast Studio has garnered acclaim for their transformative use of mycelium in repurposing urban waste into inspiring architectural structures and functional art installations. From intricately crafted furniture pieces to ambitious plans for a self-sustaining *living* architectural marvel, the studio's work embodies a profound commitment to environmental sustainability and forward-thinking design. A standout feature of Blast Studio's approach is their conceptualization of the city as an *urban stomach*, a vivid analogy that underscores their philosophy of viewing waste materials as valuable resources. Their conscientious effort to personally transport local waste materials, such as cardboard and sawdust, to their studio via bicycles, further underscores their dedication to reducing environmental impact and fostering sustainable design practices. During the engaging lecture, Blast Studio unveiled their meticulous process, offering valuable insights into their methodology, including the extrusion process principles of mycelium-infused paste and the subsequent application of bio-welding techniques for structural reinforcement. The live demonstration of the manual extrusion process provided a firsthand glimpse into the complexities involved in handling dense, mycelium-based compounds, highlighting the intricacies of their approach.

Following the lecture, I had the opportunity to engage in a conversation with P. de Pingon, one of the designers at Blast Studio. Our discussion delved into the nuances of my ongoing research, prompting a fruitful exchange of ideas and technical insights into their preferred substrates and additive materials. Pierre generously told me about their preferred combination of hemp powder and mycelium, supplemented by the strategic incorporation of coffee cup pulp, thereby providing invaluable guidance for my own experimental endeavors. The presentation also shed light on Blast Studio's digital modeling strategies, emphasizing their adept use of algorithms to craft intricate and nature-inspired geometries. Their thoughtful integration of organic elements not only fosters optimal mycelium growth but also encourages the development of robust structural forms, exemplifying their commitment to the principles of biomimicry and sustainable design practices. Furthermore, the studio's distinct aesthetic sensibilities were highlighted through their experimental incorporation of natural dyes within their creations, such as the captivating *Blue Tree* artifacts. Although limited in the case of extensive mycelium colonization, this creative exploration demonstrated the potential for generating visually stunning color gradients, symbolizing the gradual transformation from the original hues to the eventual whitening effect induced by the mycelium's growth. The stimulating discourse culminated with a thought-provoking discussion on the implications of high color contrast within the design process, underlining the potential role of color as an indicator of the organism's health status. This comprehensive perspective underscored Blast Studio's meticulous approach, reflecting their commitment to fostering a harmonious relationship between design, nature, and technology, thereby redefining the boundaries of contemporary design exploration within the realm of sustainable practices.

Img.100, 101
Some of the 3D printed vases from the "Cabinet of Curiosities" project, a collection of various different objects, sculptures and artifacts. Close up view of the developed mycelial outer skin, Blast Studio.

Img.102
The Tree Column was algorithmically designed by Blast Studio to enhance geometry structural capacity and provide optimum growing conditions for mycelium. The artifact has a ridged, undulating structure reminiscent of a tree trunk sectioned in several modules and could be harvested for mushrooms before serving as a structural building element.

Alima, N., Snooks, R. & McCormack, J. (2022). Bio Scaffolds: the orchestration of biological growth through robotic intervention. *Int J Intell Robot Appl* 6, 522-529.

Blast Studio [Online]. Available at: https://www.blast-studio.com/ (Accessed: 2 January 2023).

Biobabes, Hyper Articulated Myco-Morphs. [Online]. Available at: https://www.biobabes.eo.uk/mycomorphs (Accessed: 20 January 2023).

Biolab Studio [Online]. Available at: https://www.biolabstudio.com/ (Accessed: 19 January 2023).

Caracara Collective [Online]. Available at: nhttps://www.caracaracollective.com/ (Accessed: 30 January 2023).

Centre Pompidou (2022). Studio Klarenbeek & Dros I Art & Écologie I Centre Pompidou [Online]. Available at: https://www.youtube.com/watch?v=qN5AD7mEyHO&t=280s (Accessed: 2 May 2023).

CreativeMornings HQ (2020). Ana Goidea: Pulp Faction [Online]. Available at: https:/ /www.youtube.com/watch?v=Pu0E3-Rf7Wc (Accessed: 3 May 2023).

Dreith, B. (2022). Biolab Studio develops 3D-printed "bio scaffold" for growing mycelium. *Dezeen*, 21 December [Online]. Available at: https://www.dezeen.com/2022/12/21/biolab-studio-bio-scaffold-3d-printed-wood-mycelium-robots/ (Accessed: 19 January 2023).

Edvard, J. [Online]. Available at: https://www.jonasedvard.com/ (Accessed: 1 May 2023).

Fairs, M. (2013). Mycelium Chair by Eric Klarenbeek is 3D-printed with living tungus. *Dezeen*, 20 June [Online].

Available at: https://www.dezeen.com/2013/10/20/mycelium-chair-by-eric-kla ren beek-is-3d-pri nted-with-livi ng-fung us/ (Accessed: 2 January 2023).

Giovinazzo, A. (2022). Lamella, *Funghimagazine*, 6 March. [Online]. Available at: https://funghimagazine.it/encyclopedia/lamella/ (Accessed: 2 May 2023).

Goidea, A., Floudas, D., Andréen, D. (2022). Transcalar Design: An Approach to Biodesign in the Built Environment. *Infrastructures*, 7(50).

Hahn, J. (2022). Blast Studio 3D prints column from mycelium to make "architecture that could feed people". *Labois*, 18 January [Online]. Available at: https://www.dezeen.com/2022/01/18/blast-studio-tree-column-myceliumdesign/ (Accessed: 2 January 2023).

Hewlett Packard Enetrprise [Online]. Available at: https://www.hpe.com/us/en/what-is/swarm-intelligence.html (Accessed: 3 May 2023).

Iaacblog. (2017). Educational Programmes, Hyper Articulated Myco-Morphs. [Online]. Available at: https://www.iaacblog.com/programs/hyper-articulated-mycomorph/ (Accessed: 20 January 2023).

KickStart Your Myco-Culture - Open Source Practices from FabTextiles (2019). [Online]. Available at: https://issuu.com/nat_arc/docs/myceliumfabtextiles (Accessed: 20 January 2023).

Labios Staff reporter. (2023). Crafts NOW 2023: estas son las tendencias que han marcado la edición. *Dezeen*, 29 January [Online]. Available at: https:/labois.com/marketing/crafts-now-2023-barcelona-artesania-tendencias-innovacion/ (Accessed: 5 May 2023).

Mindcraft Project [Online]. Available at: https://mindcraftproject.com/designer/jonas-edvard/ (Accessed: 1 May 2023).

Morby, A. (2017). Structure grown from "mushroom sausages" shows potential for zero-waste architecture. *Dezeen*, 20 June [Online]. Available at: https://www.dezeen.com/2017/06/20/aleksi-vesaluoma-mushroom-mycelium-structure-shows-potential-zero-waste-architecture/ (Accessed: 1 May 2023).

Motherboard (2015). Fungus: the Plastic of the Future. [Online]. Available at: https://www.youtube.com/watch?v=jnMXH5TqqG8 (Accessed: 2 January 2023).

Mycoworks [Online]. Available at: https://www.mycoworks.com/ (Accessed: 1 May 2023).

Nature porfolio [Online]. Available at: https://www.nature.com/subjects/biomimetics (Accessed: 5 May 2023).

Scott, A. (2012). Philip Ross crafts furniture from mycelium. *SFGate*, 13 December [Online]. Available at: https://www.sfgate.com/homeandgarden/article/Philip-Ross-crafts-furniture-from-mycelium-4116989.php#photo-3871871 (Accessed: 1 May 2023).

Sensilab monash. (2018). *SensiLab Forum* - Natalie Alima [Online]. Available at: https://www.youtube.com/watch?v=-dTOd2GPa6Y (Accessed: 19 January 2023).

Thomas, G. (2012). Phil Ross Grows Furniture with Mushrooms. *Vice*, 5 December [Online]. Available at: https://www.vice.com/en/article/bmmje8/houses-of-the-future-grown-out-of-mushrooms (Accessed: 1 May 2023).

Verband 3DDruck e.V. (2021). 3DKL21 - SustainLab - 3D printing from fungi - a renewable raw material. [Online]. Available at: https://www.youtube.com/watch?v=8H8Tb9h|8h4 (Accessed: 2 January 2023).

CHAPTER 5

5.1 BENDING THE CURVE

ON CLAY 5.2 AND MYCELIUM

5.3 DEFINING DESIGNING THE FRAME

... This change in perspective entails a transition from an anthropocentric to a biocentric model, from a reactive human attitude to a proactive one that embraces a harmonious relationship with Nature ... In this intricate landscape, where a new approach is imperative not only to the discipline but also to the conception of material resources ... arises a need to reconsider the logics and the strategies for cultivating the organism and consequently the materials derived from it, owing to the new variables introduced by the integration of clay into the system ...

Img.103

BENDING THE CURVE
5.1

5.1.1
Connecting the dots

At this particular stage of the research journey, a comprehensive exploration of various themes has been meticulously undertaken throughout the preceding chapters. From an ethical perspective, the foremost emphasis lies in the imperative to steer the current economic landscape towards sustainable production models, which necessitates a thorough and conscious interpretation of the role of the design discipline within the broader societal framework. This imperative is intricately interwoven with the multifaceted dynamics associated with the role of the designer, who is being summoned to reevaluate and redefine their engagement with natural resources and to adopt a coherent and critically attuned design approach that effectively addresses the contemporary challenges and complexities of our era. In response to these imperatives, several design practices and disciplines have emerged in recent years, all underpinned by a vision that starkly opposes the conventional cultural, economic, and productive orientations dictated by the capitalist system. These practices underscore the vital importance of creativity, sustainable innovation, material experimentation, and the promotion of open-source ideologies. The first chapter of this study delved into the rich ethos of the do-it-yourself (DIY) ethic, subsequently evolving into the technological landscape of the maker culture, and the broader intersection between the realms of biology and design, which was further segmented into Growing Design, Augmented Biology, Digital Biofabrication, and Bio-design Fiction.

Notably, the discourse also revolved around the pivotal role of materials as potential agents of behavioral change, highlighting their fluid and dynamic identities, shaped by the contextual scenarios of their use and the mediating role of the designer. Petrera et al. (in E. Karana et al., 2019, p.2) aptly described these materials as *living, active, and adaptive*, thereby offering an insightful perspective that transcends the myopic lens often derived solely from the exploration of their biological and computational characteristics. In close correlation with this concept is the notion of *becoming materials*, initially introduced by Jenny Bergström et al. (2010), which posits that all materials inherently possess untapped potential and latent qualities waiting to be explored. Within this conceptual framework, the role of the designer transforms into that of a facilitator, fostering an ongoing and dynamic dialogue between humanity and nature, whereby materials are perceived as intelligent entities, forming the foundation of a symbiotic co-design relationship.

Chapter two of the research conducted an extensive and in-depth examination of the intricate nuances of clay, a material deeply entrenched in human history and geological formation, renowned for its remarkable versatility. Various aspects of clay materials were meticulously scrutinized, with a specific critical focus on the intricate thermal processes intricately involved in their transformation into ceramics. The comprehensive investigation yielded a compelling argument challenging the prevailing notion that clay is a renewable natural resource. This argument was rooted in the identification of two fundamental issues. Firstly, concerns were raised about the substantially slower terrestrial regeneration times compared to the rapid rates of human extraction and exploitation. Secondly, the firing and glazing processes were identified as chemical processes that fundamentally alter the structure of clay, rendering it into ceramics, consequently stripping it of its characteristic pseudo-coherent properties and precluding any possibility of its reuse at the initial stages of the production process. The consequential environmental impact of the high temperatures and the release of harmful substances during the various firing cycles compelled the exploration of more sustainable alternatives. The exploration culminated in the utilization of clay in its greenware state to create a diverse array of composite materials known as UBWWCs. These materials, characterized by their mechano-physical properties intricately dependent on the nuanced interplay between the clay matrix and the dispersed phase, opened up an expansive and largely unexplored design landscape, especially when combined with contemporary digital fabrication technologies.

Moreover, the extensive research journey delved deep into the introduction of the mycelium organism in the subsequent third and fourth chapters, highlighting its pivotal role in the realm of BioDesign. Mycelium-based composite materials (MBCs) emerged as a significant and highly promising biomaterial of the future, attracting substantial interest due to their sustainable production processes and the wealth of potential applications within the domain of product design. These materials represent an innovative departure from traditional resources, seamlessly integrating sustainable properties within their core framework. The role of the designer was recognized as an indispensable mediator in the intricate process of co-design between humanity and the organism, thereby unveiling a wide spectrum of design possibilities, particularly in the realm of regulating material properties. Chapter four was devoted to elucidating four insightful case studies, shedding light on the dynamic interplay between humans and nature and the myriad project outcomes that were realized based on the specific nature and scope of the interventions undertaken during the course of the study.

5.1.2

A shift towards a material perspective

Taking into account the accumulated knowledge regarding the concept of material potential along with the designer's role as a facilitator, it seems pertinent to ponder the potential design scenarios that might emerge at the intersection of the mentioned issues. The collapse of the anthropocentric model, with all its paradoxes and inadequacies, has forced us to confront the imperative need to break away from it. The *Età della velocità di fuga* (Age of Escape Velocity) (L. Caffo, 2022) has become an undeniable reality of our present, as the consequences of human actions have triggered irreversible effects on the delicate balance of our planet. In the swamp that our species has created, dragging all other life forms with it due to an obstinate resistance to change, an escape from the Anthropocene paradigm now appears inevitable. Reassessing the myth of progress, an idea of which our species has stood as the bearer, demands a shift toward a model that harmoniously integrates *economic ecology* and *environmental ecology* under a common framework. This shift necessitates the taming of the technosphere, the conglomerate of human-built artifacts and structures over time, and its harmonization with the biosphere, detaching it from the toxic dynamic in which the economic sphere thrives at the expense of the environmental sphere (K. Van Mensvoort, 2015). We find ourselves at the brink of the *planetary ceiling*, where human activity exceeds the Earth's capacity, necessitating a radical transformative act by present and future designers.

This change in perspective entails a transition from an anthropocentric to a biocentric model, from a reactive human attitude to a proactive one that embraces a harmonious relationship with Nature. Neri Oxman's concept of *material ecology* (TEDx Talks, 2015), as expounded in chapter one, resurfaces, asserting that progress is intricately linked to the human impulse to *always go back to nature* and view *evolution not as natural selection but as design*. Oxman's metaphors underline the pivotal role of the designer in the design process, which manifests as a dialogue between humanity and nature, where organisms that have never encountered each other are engineered for the first time to establish a new relationship. Oxman's attribution of an active role to designers in the process of evolution encapsulates the essence of the discipline, almost akin to a divine instrument capable of orchestrating a novel conception of a hybrid Nature designed with human assistance. Thus, a perspective emerges that mandates the adoption of a design outlook founded on the vision of Nature as the primary guide of human endeavors at various levels, not only as the ultimate output but also as the fundamental driver of the design process.

In this intricate landscape, where a new approach is imperative not only to the discipline but also to the conception of material resources, the introduction of the concept of *Material Driven Design* (MDD), coined by Elvin Karana et al. (in J. Zhou et al., 2021), assumes paramount importance. The authors define MDD as an approach to design that commences with the exploration and exploitation of material potential, diverging from a sterile and predictable view that categorizes materiality solely based on formal and functional attributes. This approach places the designer's focus on uncovering new material possibilities emanating from a perspective that conceives a material "not just for what it is, but also for what it does, what it communicates to us, what emotions it evokes, and what actions it incites." Establishing an intimate and profound relationship between designers and materials necessitates deep reflection on their perception, the meanings attributed to them, and their potential to evoke emotions. MDD serves as a tool to aid designers in "structuring, communicating, and reflecting on their actions in designing material experiences" and equips them with the necessary skills to explore, understand, define, and mobilize new material properties. In essence, MDD can be succinctly described as a methodology "to facilitate designing for material experiences when a particular material serves as the point of departure in the design process" (E. Karana et al., 2015).

Furthermore, the same authors underscore that the MDD approach is built on four foundational premises: (1) Product experiences are shaped or moderated by multiple factors, with the physical and material dimensions playing a prominent role. Consequently, in all designs, it is imperative to consider how materials influence the user experience; (2) Designing with a material necessitates a comprehensive understanding of the material itself, including its properties and limitations, cultivated through an "exploratory process of creation and evaluation" through hands-on experimentation; (3) Designing with a specific material, akin to the product design process, involves understanding the domain, establishing requirements and objectives, and channeling a concept towards product definition; (4) When the design objective is to create a material experience, the designer must chart a *journey* from the experiential qualities of the material to the visualization of the experience, from the experience to the material qualities, and finally to the products. With these premises delineated, the design methodology specific to MDD can be divided into the following primary steps: (1) Understanding the current situation, that is, how users perceive the material (based on its physical properties) at sensory, interpretive, affective, and performance levels; (2) Envisioning, where the designer conceptualizes the design intentions of the material experience after analyzing and interpreting outcomes, opportunities, and limitations; (3) Manifesting patterns, where evocative patterns are identified that can generate the material experience; (4) Creating and materializing concepts, where the designer conceptualizes and materializes ideas that transition from design intention to material or product design.

Having established the essence of MDD, the subsequent subchapter delves into the challenges and opportunities that may arise when this approach is applied to the two broader material domains addressed in the research thus far, namely, clay materials and mycelium-based composites. This marks the introduction of the central part of the thesis research, which focuses on exploring the possibilities arising from the convergence of these two materials and the implementation of product design solutions grounded in the principles of Digital Biofabrication.

MATERIAL DRIVEN DESIGN APPROACH

Img.104
Schematic representation of MDD Method with four main action steps. As depicted, the MDD process starts with a material (or a material proposal), and ends with a product and/or further developed material. The method emphasises the journey of a designer from tangible to abstract (from a material to a materials experience vision, illustrated with dashed lines and lighter colours in the bubble for Step (2), and then from abstract back to tangible (from a materials experience vision to physically manifested, further developed materials/products). Grapich redesign of the scheme in E. Karana et al., 2015.

5.1.3

An encounter, merging to evolve

Based on the insights and concepts discussed thus far, the design framework for the formulation of the personal development and design execution of the thesis research has been adequately established both scientifically and ethically. The comprehensive understanding acquired about clay materials through the previous chapters offers a lucid view of the critical challenges and inconsistencies associated with the sustainability of conventional ceramic manufacturing processes. The exploration of UBWCCs from chemical, physical, and mechanical standpoints, along with their analysis of the reduced environmental impact rooted in circular principles, presents a fresh and highly intriguing perspective, especially when this line of research intersects with the other two explored themes, namely MBCs and the practice of Digital Biofabrication. UBWCCs serve as feasible substitutes for traditional terracotta in certain applications, showcasing significant mechano-physical performance, exceptional fire retardant properties, as well as superior thermal and sound characteristics. Additionally, the circular potential of these composites, achievable through sustainable practices facilitating the recovery and reuse of waste as a dispersed phase and ensuring the biodegradability of the composite, adds another layer of sustainability. However, the challenges surrounding the broader adoption of UBWCCs in diverse usage contexts are not insignificant. Factors such as the material's relative brittleness, poor resistance to moisture and seepage pose significant obstacles. Typically, to address these concerns, a protective lime plaster is applied to the clay material, which reacts chemically with the clay but compromises its circularity, rendering it non-biodegradable and diminishing its sustainability due to the emissions involved in manufacturing these substances.

It is precisely within the context of this initial aspect that the potential opportunities arising from the convergence of UBWCCs and the mycelium organism become apparent. MBCs represent foam-like materials with exceptional mechano-physical properties, prominently featuring the water-repellent nature inherent in fungal tissues. The chitin, constituting the primary element of the wall coating of mycelium filaments, serves as both a waterproofing agent and a key contributor to mechanical durability being it responsible for responding to stress loads. From this standpoint, it can be argued that MBCs, with their thick mycelial skin, essentially function as a natural plaster that is entirely biodegradable, enabling the flow of resources back into the system at the conclusion of the material's life cycle. This attribute serves as a prime example of how the metabolic activities of biological systems can be harnessed to produce new material attributes that provide sustainable alternatives to conventional material production processes. In addition to this aspect, parallels can be drawn between the environmental conditions necessary for the proliferation of the organism in the realization of MBCs, particularly those related to high humidity, and those offered by UBWCCs during the material's deposition phase and subsequent drying. The clay mixture, owing to its substantial water requirement for malleability, offers ideal moisture parameters for mycelium development. Simultaneously, the need to maintain high relative humidity levels to facilitate the organism's growth over an extended duration creates conditions conducive to the controlled drying and shrinkage of the clay matrix. Moreover, both UBWCCs and MBCs adhere to similar principles concerning the transmission and distribution of stress loads throughout the material. These composites comprise a dispersed phase and a matrix, constituted by clay and mycelium, respectively, resulting in mechanical behavior characterized by the fiber bridging mechanism. Thus, the considerations outlined in subsections 2.3.3 and 3.3.2 regarding the influence of the dispersed phase on the mechanical properties of composites hold true for both materials under examination. Additionally, the resemblances in the potentialities and methods for adjusting composite properties through factors such as substrate nature, composition, orientation, and size imply an adaptable approach concerning the strategies that can be employed in designing the interaction between the matrix and the dispersed phase. Expanding on the discussion regarding the dispersed component of composites, it is pertinent to recall how the mycelial network's growth process hinges on the degradation of the organic substrate, serving as a nutrient base to generate the fungal matrix responsible for binding the individual particles together by filling the voids between them. On the other hand, one of the primary factors influencing the mechanical integrity of UBWCCs is the prevention of internal defects and cracks resulting from uneven shrinkage during the drying phase. Notably, the two techniques employed for fabricating UBWCCs for construction elements, namely rammed earth and adobe, necessitate complete compaction of the material within the formwork to minimize the formation of gaps between composite phases that could lead to stress concentrations within the material. These two processes are thus aimed at the common goal of achieving a material devoid of voids, albeit through fundamentally different principles. While one involves an organism that proliferates by consuming organic matter and generating a matrix that acts as a filler through progressive accumulation, the other deals with clay materials susceptible to shrinkage issues resulting in a gradual loss of matrix compactness, potentially leading to defects that impact the composite's mechanical behavior. In principle, mycelium could serve as a binding agent between the clay matrix and the dispersed phase, enhancing material performance through the development of the filamentous network within the composite.

Viewed through this lens, the potential arising from the convergence of these two types of composites becomes evident not only in terms of the new properties attainable but also with regard to defect anticipation and prevention in the design process. Lastly, the combination of a malleable material like clay with MBCs, the latter typically molded or guided during their growth, presents intriguing possibilities for achieving alternative geometries and manufacturing processes. The pseudo-coherent nature of this material, crucial for obtaining a malleable and extrudable paste, lends itself excellently to modern LDM manufacturing processes. The use of clay coupled with new digital manufacturing technologies is experiencing an exponential growth of interest from designers belonging to different fields of design. These considerations are complemented by the distinctive properties inherent in the mycelium organism, including its adhesive characteristics derived from the bio-welding process. In the upcoming subchapter, the extensive scientific exploration conducted by other researchers will be scrutinized in greater detail, highlighting their potentials, limitations, and unexplored design domains stemming from the convergence of UBWCCs and MBCs. The practical context of the MDD approach, employed in the research of other designers and forming the basis for the formulation of the impending design challenge, will also be emphasized following a comprehensive review of the current state of the art concerning clay and mycelium composites.

ON CLAY AND MYCELIUM

5.2

5.2.1

Filling the void

Although the frontier of designing with biomaterials, particularly concerning material exploration on *Mycelium-Based Composites* (MBCs), has captured significant interest among the new generation of designers, it still remains a relatively new and largely unexplored field. Numerous efforts have been made to increase knowledge of the biofabrication processes of mycelium artifacts, primarily focusing on understanding the dynamics and factors that influence the achievable results from the perspective of the material properties of composites. This has led to research concentrated on defining strategies for adjusting macroscopic aspects of the material that could influence design outputs in terms of compressive and tensile strength, stiffness, elasticity, density, dimensional uniformity, water absorption, thermal and acoustic insulation. Simultaneously, some artists, scientists, and designers have explored alternative fabrication methods for MBCs, which could unlock new design potentials related to the use of modern digital fabrication technologies. However, on the other hand, regarding the possibility of integrating the knowledge gained in the field of design on mycelium with other material horizons, the available scientific literature seems significantly limited. In particular, reconnecting with the reflections just made about the potential offered by the encounter between mycelium and clay in the greenware state, it becomes evident that this is a field of intersection with only a handful of examples to draw from.

Given the experimental nature of the investigation conducted by these authors, it inevitably follows the design method of Material Driven Design (MDD) where material exploration is based on an in-depth knowledge of the material built by *tinkering* with it (E. Karana et al., 2015). The research available in the scientific landscape mainly correlates with the field of architecture, neglecting potential applications in the field of product design. The reasons for this bias can be traced to the familiarity that this material has with the former rather than the latter. In the chapter devoted to clay, it was emphasized that this material has a historical association with the construction sector and is supported by specific digital fabrication processes tailored to its characteristics such as LDM technologies. Moreover, the concept of *Mycoremediation*, underlying the design intent elucidated in most available research on clay and mycelium, has been put forward by Paul Stamets (TEDx Talks, 2008). Mycoremediation describes a method of restoring and regenerating contaminated soils that leverages the natural decomposition capabilities of fungal mycelium. The unique capacity of fungi to break down chemical pollutants and heavy metals, coupled with their efficient filtration of contaminated water, plays a pivotal role in the regeneration of ecosystems. Analyzing the state of the art related to the combination of clay and mycelium, it is crucial to highlight the behavioral dynamics of the new material generated by the introduction of the organism and the resultant design challenges.

^ Img.105, 106
On the left image material sample from bioBaldaccini investigation, programmed stacks of clay and mycelium. On the right one visualisation of the “digital seismograph” Rhino- Grasshopper tool, Adrien Rigobello.

After conducting thorough research, the earliest available scientific literature mentioning the combined use of clay and mycelium was authored by Adrien Rigobello in 2016. Rigobello’s work, *bioBaldaccini* (2016), primarily focuses on the design of a digital tool aimed at analyzing the behavior of the clay matrix during the shrinkage phase. The project’s underlying premise is rooted in understanding the impact of the matrix’s microstructure on facilitating the additive manufacturing of intricate geometries. The initiative to encourage mycelium growth serves as an effort to counteract the formation of internal cracks and enhance the material’s behavior during the drying process, thereby expanding the design possibilities. The resulting tool, named the *digital seismograph*, comprises a Rhino-Grasshopper tool capable of monitoring the internal microstructure of both inoculated and non-inoculated clay samples with the organism, assessing how it changes as the biomaterial dries. Rigobello’s work was conducted within the context of the IAAC and Noumena’s On-Site Robotics pavilion installation. Within the field of innovative biomaterials, particularly fungal-based composites, Adrien Rigobello is recognized as one of the most seasoned scientific experts. His Mycobosci research has significantly contributed to advancing knowledge about strategies for regulating the properties of MBCs, evident through numerous projects and scientific publications. While Rigobello’s work stands as one of the initial endeavors linking clay and fungal materials, addressing critical concerns such as shrinkage issues, his investigation lacks a definitive demonstration of the compatibility between mycelium and clay and fails to outline guidelines for fostering the growth of the new material. It is crucial to note that clay, primarily composed of elements like silica, alumina, magnesia, iron, potassium, sodium, and calcium, is generally unsuitable for colonization by the organism, which primarily feeds on organic polymers such as lignin, hemicellulose, and cellulose. Hence, there arises a need to reconsider the approach and strategies for cultivating the organism and consequently the materials derived from it, owing to the new variables introduced by the integration of clay into the system.

Img.107
Material sample from the Claycelium material investigation. Spreading of the organism on the clay matrix

5.2.2

Claycelium by Justin Sherinberg and Mert Gonul

From this perspective, the very first pioneering research delving into the effectiveness of mycelium growth on clay materials is represented by the project *Claycelium, living structures* (2019), developed by Justin Sheinberg and Mert Gonul during the 2018/19 academic year at IAAC, Institute for Advanced Architecture of Catalonia, in collaboration with IIT, Italian Institute of Technology. The primary goal of the project was to establish a new extrudable composite material using LDM technologies, showcasing enhanced structural properties in comparison to greenware clay by integrating mycelium. The successful outcomes of the research were oriented towards conceptualizing low environmental impact architectural structures capable of functioning as self-sustaining food-producing systems. Embracing the practice of Digital Biofabrication through an interdisciplinary Material Driven Design approach, Claycelium represented a comprehensive exploration bridging aspects of architecture and agriculture. The research methodology was meticulously structured, encompassing various phases, each meticulously tailored to address specific objectives. These phases included: (1) Assessment of mycelium's attraction to diverse organic substrates; (2) Analysis of the efficacy of combining the organism with various nutrients and substrates; (3) Exploration of mycelium's ability to propagate within the clay matrix; (4) Evaluation of the impact of different viscosifying agents on the extrudability of the printing mixture; (5) Examination of different techniques for integrating mycelium and clay; (6) Assessment of the germination potential of specific legumes based on the proportion of inoculated soil in the mixture.

The research findings highlighted sawdust, hemp, and coffee grounds as optimal substrates for the mixture, with agar emerging as the most effective nutrient during the early stages of cultivation. Both strategies for combining clay and mycelium were successful in achieving the intended colonization objective, with the method of filling cavities leading not only to the colonization of clay but also the generation of fruiting bodies, as illustrated in the photographic documentation. For the final samples, the printing mixture was formulated in proportions of Clay 30%, Water 18%, Coffee grounds 20%, Sawdust 20%, and Inoculated Spawn 12%. Another key consideration underscored in the research was the criticality of promoting porosity and facilitating oxygen exchange through the geometric design, contributing significantly to the successful colonization of the samples. These colonized samples were subjected to a series of tests to ascertain their performance compared to control samples made solely from clay. The immersion test demonstrated the water-repellent properties of the claycelium material, showcasing its resistance to seepage over an 8-minute duration, unlike the control sample that melted under similar conditions. In the tensile strength test, both the clay-only and colonized clay modules demonstrated differing degrees of resilience when exposed to forces of 105PSI and 125PSI, respectively, with the colonized clay exhibiting a remarkable 19 percent increase in tensile strength values compared to the control sample. Furthermore, the research explicitly outlined the operational conditions, emphasizing the use of pasteurization and sterilization with 90% isopropyl alcohol to maintain the sterility of the ingredients and equipment. Operating in a non-sterile environment was an intended choice, enabling the replication of the research process by a broader audience. Stated growth conditions included a temperature range of 20-28°C and humidity levels between 70-90%, ensuring optimal and conducive conditions for the successful execution of the research project. The timeframes for growth pertaining to the initial stages of ingredient selection were initially 14 days, subsequently reduced to seven days for the incubation of the printed samples with the inoculated mixture. Notably absent, however, is any indication of whether the samples underwent a deactivation phase of the organism via temperature treatment.

The extensive research conducted by Justin Sheinberg and Mert Gonul stands as a significant scientific milestone, primarily showcasing the potential of integrating clay and mycelium. The research not only effectively demonstrates the compatibility between the two materials but also pioneers a comprehensive methodology for the selection, cultivation, and biofabrication processes. However, the progress of experimentation remains constrained, confined to illustrating the growth of the organism solely on samples characterized by simple geometries and relatively small dimensions. While the precise size remains unspecified, a careful analysis of the photographic documentation suggests the utilization of small volumes and heights not exceeding 10cm. Notably, the observed growth of the organism on these specimens appears less robust, with the formation of a substantial mycelial layer seemingly absent, diverging from the typical observation in the cultivation of traditional MBCs. Moreover, the envisioned utilization of more intricate geometries, intended to facilitate gaseous exchanges between the organism and its surrounding environment, presents a perplexing scenario. Based on the visual evidence provided, the growth of the organism is either barely discernible or entirely absent, raising ambiguous questions regarding the underlying factors influencing this outcome.

Img.108
3D printed clay artifact exhibiting signs of a principle of organism growth within the corrugation areas created by the intricate geometries. The surface in contact with the printing plane, here observed from above, shows no signs of colonization by mycelium.

The research culminates by postulating the potential for the designers to create large-scale architectural elements or structures, such as masonry or columns, utilizing such composite material as urban food-producing systems. However, the full realization of this vision necessitates further comprehensive research and investigation to evaluate the scalability of the process and ascertain the actual feasibility of generating fruiting bodies or sprouting seeds dispersed within elements that have undergone progressive drying phases. This also invariably prompts critical inquiries into the methodologies for deactivating hypothetical large artifacts, essential for preventing the gradual degradation of the developed fungal layer and preserving the unique properties acquired by the composite material.

5.2.3

Zoetic Morphologies by Doruk Yildirim

During the 2018/19 academic year at IAAC, Institute for Advanced Architecture of Catalonia, Doruk Yildirim's *Zoetic Morphologies* (2020) presents an intriguing project that delves into the potential fusion of clay and organism. This venture aims to pioneer a living architecture using a composite material of greenware and fungal mycelium for LDM additive processes. The project's core focus lies in crafting dynamic masonry systems capable of housing organisms to create dense insulating biomass, optimize building envelopes, and facilitate the biodegradation of agricultural waste. The research methodology is structured around three key areas: developing a cohesive and efficient material system, devising tailored additive manufacturing strategies, and crafting geometries using generative algorithms and growth simulations to facilitate data-driven systems exploring various factors such as water and wind channeling, porosity, and diverse incubation rates. Highlighting the pursuit to create a blend and design protocol capable of minimizing and withstanding external pathogenic threats - crucial for fostering organism growth - this section will delve into the execution of this objective during the material experimentation phase and the adopted strategies. To ensure the most sterile conditions possible, an enclosed growth chamber was established early on, equipped with a humidifier and an aquarium heater to monitor and maintain consistent internal environmental settings. Additionally, the growth tent underwent a weekly 15-minute UV light treatment to eradicate external contaminants while safeguarding the cultures. Cultures and larger prototypes were housed in Petri dishes and other sizable containers within the chamber. To foster a sterilized work environment, all instruments were sanitized with isopropyl alcohol before use, and plastic gloves were employed.

Initial phases of material experimentation concentrated on pinpointing the optimal substrates for Pleurotus Ostreatus strain colonization. Petri plates housing pasteurized substrates were inoculated and left to incubate for 24 days, revealing that wheat bran and straw facilitated a higher organism growth rate compared to rye, chitosan, and cellulose. With these substrates, a replicated experiment with a pH level of 9 was conducted to assess mycelium's capacity to thrive in high pH environments, aiming to mitigate contamination from other external agents. Results indicated the mycelium's adaptability to substrates with these pH values, outlining preliminary strategies to preempt or contain potential contamination. Furthermore, an evaluation of mycelium's ability to propagate under low humidity conditions (40%) was performed on clay artifacts externally coated with inoculated substrate. This analysis demonstrated limited or sluggish organism growth and hindered pathogen proliferation due to insufficient moisture levels. Subsequently, amalgamating the preceding considerations, a further experiment was conducted, filling the cavities of two clay-only molded artifacts with inoculated, unsterilized substrate and subjecting them to an 8-day incubation at 60% humidity levels. The first artifact retained the original substrate pH, while the second was adjusted to a pH of 10. The growth of the fungus solely on the second artifact, despite contamination of the first, demonstrated that when confronted with pH values unsupportive of the proliferation of external pathogens, the mycelium can outcompete potential contamination as it thrives equally at these pH levels. Following this exploration of materials, the subsequent phase concentrates on conceptualizing additive manufacturing strategies, either concerning the blending of the compound prior to insertion into the printing reservoir, or utilizing a dual-tank printer capable of depositing diverse materials depending on the functionality of the implicated layers.

As highlighted by the author in the research, the investigation into printing strategies for the clay and mycelium compound was hampered by the Covid-19 pandemic, impeding access to space and equipment. This hindered a critical advancement in the research aimed at demonstrating the effectiveness of printing processes involving the deposition of a mixture comprising clay and mycelium, with the previous experiments envisioning cavity filling subsequent to the exclusive clay printing. Despite this investigative void, the research contributes vital insights regarding the behavior of the organism in low-humidity environments and uncolonized substrates with differing pH values. In this context, a further clarification is necessary, based on the knowledge acquired by the undersigned through the scientific study conducted so far. Although working under low humidity conditions may prove beneficial in substantiating evidence for the conducted experiments, such conditions are incompatible with preserving the filamentous structure developed by the organism. While a reduction in humidity levels can indeed induce *hibernation* in the mycelium (D. Alemu et al., 2022), enabling its growth to be resumed by subsequently restoring the conditions to suitable levels, exposing the organism to an unfavorable environment inevitably leads to the degradation of the structure that had been formed until that point, resulting in a decline in the composite's mechanical and physical properties. Considering this contemplation, the selection of the method for deactivating the organism hypothesized by the author of the research for the proposed architectural structures appears rushed and inaccurate. The research concludes with the design of various geometries, generated through computational modeling, to simulate the organism's growth on them and optimize it in anticipation of the interaction between architectural elements and atmospheric phenomena like water and wind.

Img.109, 110, 111
On the left page spreading of the organism on the clay matrix originating from the substrate employed as a filling and going towards the external walls. On the right page progressive colonisation of the artifact performed by the mycelium through its development originated from the substrate dispersed on the surface.

^ Img.112, 113
^ Close-up view of fruiting bodies sprouting through the clay matrix following its complete colonisation by the organism.

5.2.4

3D Printed Bio-Hybrid Structures by Claudia Colmo

The next study in focus is 3D Printed Bio-Hybrid Structures conducted by Claudia Colmo at the Royal Danish Academy in Copenhagen (2020). This project delves into the burgeoning realm of bio-hybrid architectures, which are defined as “ssystems that symbiotically combine artificial and technical components with living complexes to achieve architectural objectives” (C. Colmo, P. Ayres, 2022, p.2). The authors’ definition of their work implies that the artifact, straddling the line between a living organism and an architectural element, assumes roles beyond its structural functions, expanding its domain to the realm of mycoremediation. The proposed prototype of a temporary landscape restoration structure seeks to establish a framework wherein co-designing with living organisms fosters sustainable dynamics, with mycelium serving as a remediation agent. Echoing the concept of bioremediation, another key theme of the project is to underscore the circular potential of construction approaches that embrace *in situ* resource utilization and zero-waste principles. The research primarily concentrates on formulating additive digital fabrication strategies that accommodate the design constraints arising from the integration of the organism, both in technical and methodological aspects. In this context, the study follows two main research threads. The first thread aims to develop a clay-based composite mixture suitable for extrusion through LDM processes, while also defining the relevant printing parameters. Notably, the research introduces a novelty by incorporating bioadditives to enhance the biocompatibility between composite phases and facilitate the extrusion process. The second phase involves experimenting, through prototyping, with specific geometric and environmental parameters conducive to mycelium colonization, even under non-sterile cultivation protocols.

Compared to the initial phase, the research primarily concentrates on formulating an extrudable blend consisting of clay, an organic dispersed phase, and additional substances. The material experimentation conducted is aimed at assessing the viability of the blend in terms of its extrudability, viscosity, and susceptibility to breakage. The first set of formulations considered the incorporation of two thickening agents, namely guar gum and xanthan gum. These natural additives, available in powdered form, are respectively derived from guar seed and from the fermentation of glucose or sucrose by the bacterium Xanthomonas campestris. Xanthan gum, particularly, has been employed as a stabilizing biopolymer in previous studies investigating the regulation of shrinkage behavior in clay materials. These studies have demonstrated that clay treated with xanthan gum exhibits increased fracture resistance and reduced susceptibility to cracking compared to the untreated counterpart (O. Barani and P. Barfar, 2021). The preference for xanthan gum among other thickeners for this purpose is attributed to its superior stability across a range of temperatures and pH levels (M.J. Zohuriaan and F. Shokrolahi 2004, N. Latifi et al. 2016, S. Muguda et al. 2017 in O. Barani and P. Barfar, 2021), as well as its stronger gelling capabilities in comparison to other gums (S.I. Laneuville et al. 2006, N. Latifi et al. 2016 in O. Barani and P. Barfar, 2021). The initial recipe (A) tested by the researchers comprised clay, water, and both gelling agents, but was discarded due to its excessive viscosity, making extrusion challenging, and its brittle nature once printed. The subsequent recipe (B) involved the addition of glycerol as a lubricant, molasses as an additional thickener, and hay fibers as an organic reinforcing component measuring 15-20mm in size. These components were combined in the proportions of 74% clay, 0.4% xanthan gum, 0.2% guar gum, 1.5% hay, 0.9% molasses, 1% glycerol, and 22% water, resulting in a formulation with favorable viscous and extrusion properties. Building upon this formula, a modified version (C) was tested, integrating grain spawn into the mixture, which led to an excessively thick consistency and hindered the organism's colonization. Consequently, recipe (D) included the addition of perlite, an expanded volcanic rock granule, to reduce density and enhance aeration within the material. The mixture (D) utilized in the subsequent stage was composed of 60% clay, 0.4% xanthan gum, 0.2% guar gum, 20% water, 2% hay, 1% glycerol, 1.4% molasses, 5% perlite, and 10% inoculated grain spawn. The mixture (D) allowed the deposition of 3-4mm layers via a 7mm nozzle at a pressure of 1.5 bar. To maintain the moisture content of the prototypes and foster organism proliferation, the prototypes were kept under humidity conditions of 60-70% and were periodically rehydrated through spraying every two days.

With the mixture composition set, the second phase concentrated on exploring the impact of geometries and clay coupling techniques to optimize mycelium growth on the artifact, leading to the creation of two distinct prototypes. The first prototype exhibited a layered internal structure featuring centrally positioned inoculated straw with vertically arranged fibers, surrounded by layers of uninoculated chopped hay and an outer layer of uninoculated clay. In contrast, the second prototype showcased an inner layer of non-inoculated straw, succeeding layers of uninoculated chopped straw, an inoculated clay layer formulated as per recipe (D), additional layers of chopped straw, and a final layer of clay (A), all uninoculated. Both prototypes were topped with soil to maintain moisture levels and prevent rapid drying of the substrate within. Notably, the first prototype underwent inoculation during filling via the use of straw, while the second underwent pre-inoculation during the printing stage, incorporating grain spawn and chopped straw into the mixture. Placed in a growth environment at 27°C and in contact with a glass wall for observation, the first prototype demonstrated rapid and consistent mycelium growth. After 2 days, visible hyphae emerged, followed by clay colonization at 7 days, complete object colonization at 20 days, and the appearance of a second generation of fruiting bodies at 41 days. Conversely, the second prototype exhibited uneven and inconsistent growth over the 31-day period.

This research represents a significant advancement in understanding mycelium clay composites, addressing the issue of material shrinkage by integrating thickening agents into the printing mixture. This addition serves to prevent cracking and enhance the composite's extrudability. Although the study successfully established a recipe, it failed to demonstrate the organism's ability to proliferate from the mixture itself and create a thick fungal skin such the one observed in MBCs manufacturing processes, highlighting the potential of utilizing the mixture for spreading mycelium from an inoculated substrate layer. Furthermore, the prototype with the printing mixture as the inoculated component did not exhibit satisfactory growth during the incubation period. Notably, no strategy for deactivating the organism was mentioned, as the primary focus lay in leveraging the fungus's bioremediation properties for the fabrication of temporary structures, rather than creating long-lasting structural elements.

^ Img.114
^ Through the use of a transparent surface, the progression of the organism through the different layers of the artifact could be monitored until colonization of the clay matrix was achieved just as would be observed if one were to dissect the object.

Img.115
Material samples from Mycera material investigation. The module cavities are filled with the inoculated substrate and left to grow, after the full development of the organism the pieces are connected togheter by exploiting the organism as a binding agent. Among the project investigated Mycera is the only one design-related which contemplates the assembling of 3d printed clay artifacts through the mycelium's methabolic processes.

5.2.5

Mycera by ShapeLab

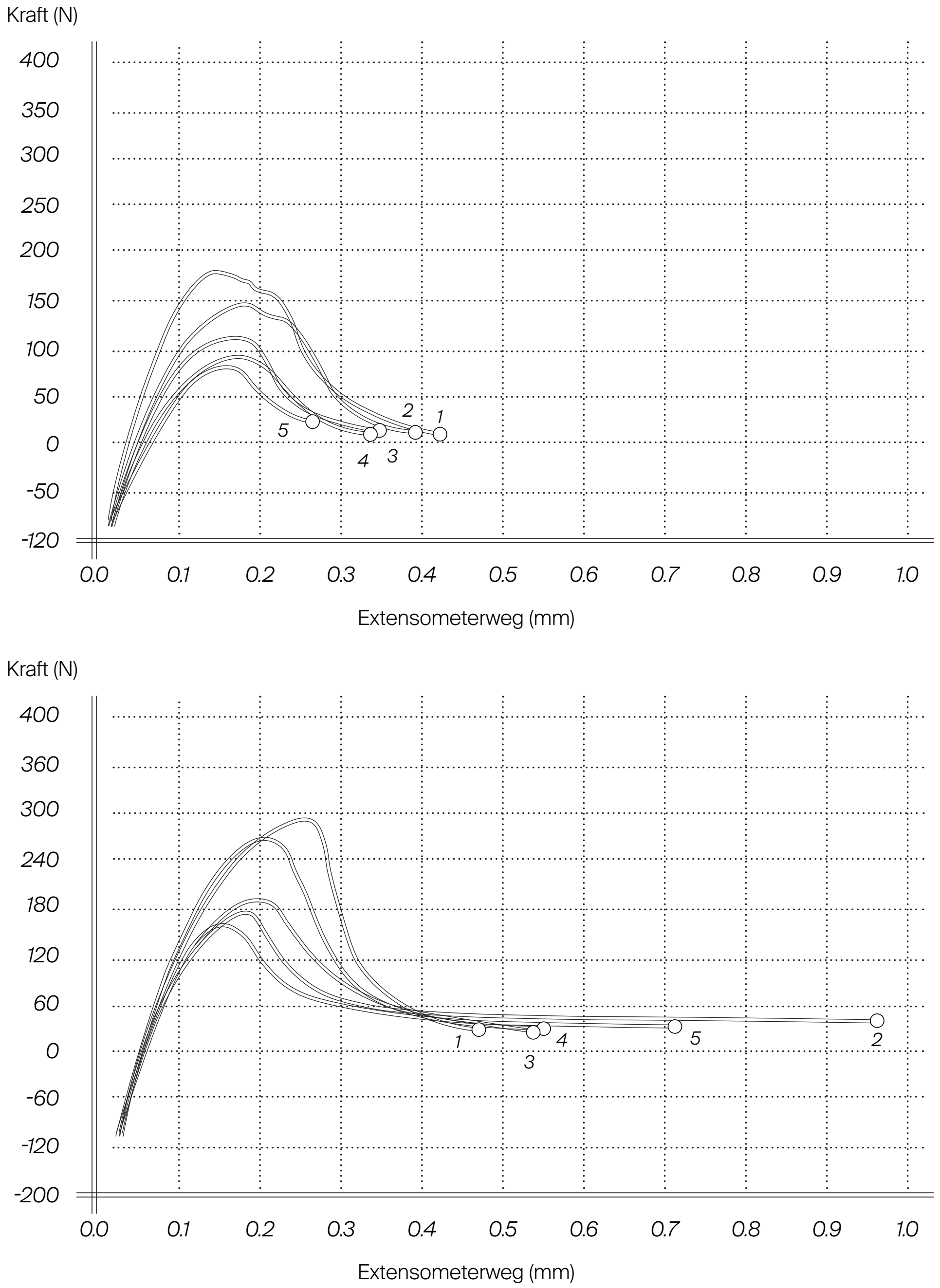
Before proceeding with the proposal for a personal design path, let's delve into the insightful case study of Mycera (2021) by ShapeLab, a research group at Graz University of Technology in Austria. Among the various experiments exploring the combination of clay and mycelium, Mycera stands out for its compelling objectives and remarkable outcomes. The project involves the creation of a composite material utilizing raw clay, ceramic, and mycelium. Its primary aim is to explore production models that integrate digital fabrication technologies with an organic growth-oriented design approach. Integral to this endeavor are the computational tools employed to anticipate mycelium growth, which is interpreted as a strategic means of intelligently distributing reinforcing fibers within the component. This characteristic distinguishes it from materials that do not possess a growth aspect.

The study's methodology unfolds in four key phases. The initial phase focuses on material experimentation, aiming to determine suitable combinations of organic substrates and their proportions to ensure proper nutrient supply and ease of mixture extrusion. Various substrates, such as sawdust, bleached cellulose, and unbleached cellulose, were considered in conjunction with clay and two fungal strains, namely Pleurotus Ostreatus and Ganoderma Lucidum. Sawdust emerged as the optimal substrate due to its controlled particle size and availability, in contrast to the contamination challenges encountered with Ganoderma Lucidum. Consequently, Pleurotus Ostreatus, characterized by a higher growth rate and density, was selected. Once the main ingredients were defined, the mixture was prepared by combining clay and substrate in a 7:1 ratio, with the addition of water accounting for 35 percent of the total weight. The authors emphasized the importance of maintaining low hydration levels to minimize material shrinkage during the drying process, while ensuring a sufficiently dense mixture capable of realizing embossed geometries. The artifacts were printed using an uninoculated mixture comprising clay, water, and sawdust in the prescribed proportions. While prints using inoculated mixtures were also attempted, the approach of printing uninoculated artifacts, followed by subsequent stages of drying, sterilization, rehydration, and eventual inoculation and incubation, was considered the most effective means of maintaining sterile conditions throughout the process. A range of diverse geometries were produced, with the inoculated substrate dispersed on the surface or utilized to fill the cavities, maintaining a consistent 10% inoculum rate for this purpose. The second and third stages focused on creating two sample types - one with the composite material and the other as a control sample with clay only - and conducting specific tests to measure changes in tensile strength along the extrusion axis and bonding force between printed layers. The models, generated using a customized Grasshopper script, were printed with a 4mm nozzle and a 6-bar pressure, exceeding the typical standards for clay material printing due to the dispersed phase and low water content. The samples, measuring about 60x170x15 mm, underwent a sequence of treatments, including drying, sterilization, rehydration with sterile water, and a fourteen-day incubation within microperforated bags, attached to the inoculated substrate either through surface dispersion or cavity filling. The test results for the mycelium-colonized artifacts indicated an average increase of 66.62 percent in tensile strength along the extrusion axis (from 204.28 N to 278.3 N) and 32.34 percent in bond strength between printed layers (from 93.14 N to 110.9 N) compared to the control sample. These findings highlighted how the organism's proliferation, combined with the mechanical input of the dispersed phase, contributed to a stronger adhesion and denser matrix compared to that observed in the clay-only sample. Additionally, visual microscopic analyses on randomly sectioned pieces demonstrated the progression of hyphae within the clay walls, ranging in size from 2.5 to 9.5 mm.

Contrastingly, the final phase of the investigation was dedicated to constructing a structure comprising interconnected modules by exploiting the bio-welding properties of the organism. Computational models, utilizing the Meatball algorithm, aided in predicting the organism's expansion and adjusting the artifact's design accordingly. The proposed structure was divided into two element types— bars and joints— both crafted from the same non-inoculated composite mixture containing 77.5 percent clay and 22.5 percent sawdust. Both module types underwent an identical process, encompassing printing, drying, sterilization, rehydration, inoculation, and incubation at 24°C with 80% humidity. Following a two-week period, the bars underwent a firing procedure of 6 hours at 600°C, followed by 2.5 hours at 960°C to enhance their structural integrity. The bars, in the bisqueware state, displayed a

STRESS-STRAIN BEHAVIOUR OF MYCERA COMPOSITE

Img.116, 117
Comparing the load curves regarding tensile strength along the extrusion axis of the individual samples without (top) and with (bottom) mycelial growth. The test results for the mycelium-colonized artifacts indicated an average increase of 66.62 percent in tensile strength along the extrusion axis (from 204.28 N to 278.3 N) and 32.34 percent in bond strength between printed layers (from 93.14 N to 110.9 N) compared to the control sample. Grapich redesign of the schemes in Julian Jauk et al., 2021.



highly porous structure due to the combustion of organic components such as sawdust and mycelium. Refilled with inoculated substrate, they were placed in contact with the still-growing nodes while in the greenware state, allowing them to grow for an additional 14 days to facilitate the bio-welding process. Subsequently, the assembled structure was air-dried at room temperature.

The Mycera research conducted by ShapeLab significantly advances the understanding of clay and mycelium composites, by pioneering the assembly of artifacts in this material by harnessing the organism's properties. Notably, it demonstrates the hyphae's capability to permeate and diffuse within the clay matrix, even through relatively thick walls, as confirmed by microscopic observations. This observation holds true for both unfired clay and ceramic modules, where the macro porosity resulting from the burning of organic phases is effectively replenished by the growth of the fungal matrix. Furthermore, the research highlights the potential of mycelium in facilitating connections between different pieces, even in cases where surfaces do not perfectly match. This emphasizes the organism's capacity to establish novel assembly methods devoid of artificial joints, accommodating and tolerating imperfections. Within the realm of LDM technologies, using the organism as a connecting agent for assembling artifacts of discrete dimensions unveils unprecedented possibilities, partly liberating part geometries from constraints outlined in subsection 2.4.2 related to the material's fluid and nonstructural nature during deposition. Additionally, the incorporation of the fungal network within the clay matrix elevates the mechanical properties of the composite material, enhancing its tensile strength along the extrusion axis and bonding strength between the molded layers.

In spite of the notable scientific strides outlined in the investigation, the authors themselves acknowledge the challenges in maintaining process sterility during the blend's printing phase. In the context of this study, the choice of inoculating clay had to be discarded, elongating the process timeline and introducing additional emissions, notably from the use of the autoclave for the sterilization cycle. Ensuring an extrudable blend capable of facilitating effective colonization and achieving a refined surface finish remains an unresolved concern. This issue is significant and intricately linked to the attainable output quality, as evidenced by the photographic documentation revealing non-uniform colonization of the ceramic bars within the final assembled structure, primarily near the unfired clay nodes. This discrepancy arises from the fact that while hyphae demonstrate the ability to propagate within the clay matrix, the ceramic material itself, once fired and stripped of its previous organic components, proves entirely inert. Consequently, the assembly approach outlined in the Mycera research necessitates the filling of cavities with inoculated substrate to facilitate bio-welding between different pieces, as observed in both bars and joints. Nevertheless, the effectiveness of unfired clay joints, when utilized in the greenware state as connecting elements of the structure, is demonstrated. This observation theoretically implies that properly colonized and qualitatively acceptable artifacts composed of unfired clay and inoculated substrate can potentially be utilized to construct structures of greater dimensions, integrating the organism's co-design role as a central aspect.

V V Img.118, 119
Assembled structure composed of fired clay bars connected through unfired clay nodes. The interdisciplinary research combined digital fabrication with the use of mycelial growth to manufacture building components conceived to gradually allow a substitution of cement-based binders in the construction process.

DEFINING, DESIGNING THE FRAME

5.3

5.3.1

Analysis of opportunities and area of intervention

Up until this point, the research undertaken has progressively delved into various ethical, sustainable, and methodological issues in the domain of design practices. It has also explored traditional and innovative production processes, as well as materiality, with a specific focus on principles inherent to chemistry, physics, and other related disciplines. Particularly, Section 5.2's attempt to survey the potential fusion of MBCs and UBWCCs, in conjunction with the initial considerations in Chapter 5, laid a solid foundation for personal reflections aimed at defining an original design direction and addressing challenges aligned with the acquired knowledge.

These outlined works have undeniably enriched scientific understanding regarding the compatibility between clay and mycelium, providing significant evidence about the behavior of the materials involved, considering the methodology employed during the experimental phase. However, as indicated by the critical reflections at the end of each examined case study, the novelty of the investigated field and the relative scarcity of scientific knowledge about it have influenced not only the quality of the outcomes but also the trajectory of the research itself. Most of the studies primarily focused on substantiating the feasibility of creating a hybrid composite between MBCs and UBWCCs, achieving surface growth of the organism on clay bases through various colonization strategies. Apart from Mycera, these projects showed limited interest in the development of a colonizable printing mixture, primarily conceptualizing a range of innovative architectural systems that could function as food-producing systems or facilitate myco-remediation and land reclamation. However, due to the speculative nature of these endeavors, despite adopting an MDD approach for material knowledge acquisition, the foundation remains somewhat unstable owing to the novelty of the investigative field resulting from the convergence of the two materials and the presence of numerous unexplored aspects. Notably, Mycera, distinguished as the only work not directly associated with architecture, is the first to address fundamental aspects on a more practical and tangible scale. Specifically, the practical perspective addresses the design challenge of constructing structures using LDM technologies, leveraging the organism's metabolic properties to actively participate in the process of assembly. The mycelium's active participation in the process, viewed through the lens of BioDesign as a collaborative effort between humans and nature, generates tangible design results within the convergence of MBCs and UBWCCs, an extensively explored theme since the initial chapter.

Considering the reflections on the various issues explored thus far in the journey, particularly those that surfaced in Chapter 5, a general framework of the objectives proposed for the investigation within the MBCs and UBWCCs intersection can be delineated. With the aim of advancing scientific knowledge in the realm of creating these hybrid composites, the forthcoming experimentation will adhere to the MDD approach, focusing notably on stages 1, 2, and 4 of the process—namely, *understanding the material*, *creating materials experience vision*, and *design material/product concept*. During the initial phases, all the theoretical research conducted thus far concerning the materials and processes involved, essential for acquiring comprehensive preparatory knowledge of the operational context, should be incorporated. However, both phases require an additional layer of in-depth fieldwork that would have been required anyway by *getting one's hands dirty* with it, but which given the nature of the material that can still be considered almost completely unexplored, requires a greater effort. Since it is not only a matter of understanding its sensory, interpretative and performance qualities but in this sense one is almost called upon to invent and shape them and the process methodology. Subsequently, based on the results, design opportunities and limitations revealed by the materials experimentation, the feasibility of the design objectives will be verified. Finally, in the final stage of the project, the focus will shift to the realization of the conceptual foundations of the experimentation objectives, moving from the design intention to the implementation of the concrete product design. Thus, the objectives of the present research can be briefly summarized as follows:

- Obtaining a claylish mixture to be printable through LDM technology and devising a methodology that fosters mycelium colonization of printed artifacts, potentially involving clay inoculation prior to the mixture deposition process;

- Achieve a substantial fungal matrix quality to demonstrate effective colonization of the mixture at a higher level than observed in the case studies in Chapter 5, potentially being comparable to that observed in MBCs;

- Exploiting mycelium's metabolic processes to fabricate artifacts with discrete mechanical and physical properties while retaining the clay in its greenware state. The intersection between MBCs and UBWCCs materials aims to create a novel hybrid material that surpasses not only raw clay but also conventional UBWCCs in terms of performance and strength;

- Simultaneously, the previous intent aligns with the goal of significantly reducing the environmental footprint resulting from the production of such artifacts compared to the equivalent in ceramic, as they won't undergo firing processes. Moreover, crafting an artifact from a hybrid composite of raw clay, dispersed phase, and mycelium aims to ensure the complete biodegradability of the material at the conclusion of the product's life cycle;

- Lastly, within the context of LDM digital fabrication processes, the aim is to fabricate an artifact of discrete dimensions designed accordingly to a modular logic of fabrication and assembly defined on the bio-welding properties of mycelium. The assembly phase, rooted in collaboration with the organism, intends to free the final design output from size and geometry constraints imposed by the fabrication tool, thereby removing the need for large LDM printers to create objects of any dimension. In this sense, the realization of this artifact is intended as a demonstrative manifesto of a design approach that contemplates a mature involvement of living organisms within the logic of additive manufacturing processes, demonstrating in concrete terms the potential of Digital Bio-fabrication practice.

3D WASP. (2023). 3D printing Mycelium reinforced structures I MyCera [Online]. Available at: https://www.youtube.com/watch?v=RMdPgJJPOew (Accessed: 28 October 2023).

3D WASP. (2023). Utilizzare il micelio per rinforzare strutture in argilla stampate in 3D [Online]. Available at: https://www.3dwasp.com/mycera-stampare-in-3d-strutture-rinforzate-dal-micelio/ (Accessed: 8 October 2023).

Alemu, D., Tafesse, M., & Mondai, A. K. (2022). Mycelium-based composite: The future sustainable biomaterial. *International journal of biomaterials*. Available at: https://royaldanishacademy.com/project/3d-printed-bio-hydrid-structures (Accessed: 24 January 2023).

Barani, O. R., Barfar, P. (2021). Effect of xanthan gum biopolymer on fracture properties of clay. Journal of *Materials in Civil Engineering*, 33(1), 04020426.

Caffo, L. (2022). Velocità di fuga (1a ed.). Torino: Giulio Einaudi editore

Colmo, C. (2020). 3D PRINTED BI0 HYBRID STRUCTURES_Claudia Colmo, Phil Ayres [Online]. Available at: https://www.youtube.com/watch?v=AWWu5hT877k (Accessed 2 January 2023).

Colmo, C., Ayres, P. (2020, September). 3d Printed Bio-hybrid Structures: Investigating the architectural potentials of mycoremediation. In Anthropologic-Architecture and Fabrication in the cognitive age: The 38th Conference on Education and Research in Computer Aided Architectural Design in Europe (pp. 573-582). eCAADe.

Colmo, C., Ayres, P. (2022). Remediating architecture: A bio-hybrid approach employing fungal mycelium. In Structures and Architecture A Viable Urban Perspective? (pp. 27-34). CRC Press.

Dedenroth, N. (2020). Zoetic Morphologies: 3d printed active wall systems through mycelial biomass [Online]. Available at: https://www.youtube.com/watch?v=PlitVZajWJM (Accessed: 21 January 2023).

HBBE Hub tor Biotechnology in the Built Environment. (2021). Mycology tor Architecture: 3D Printing Mycelium Composites [Online]. Available at: https://www.youtube.com/watch?v=971AHk4V J4k&list=PLS6cw _ VBkY6SIJKp2VuFAQKOsaNPCQH5a (Accessed: 2 January 2023).

Iaacblog. (2019). Educational Programmes, Claycelium_living structures. [Online]. Available at: https://www.iaacblog.com/programs/claycelium/ (Accessed: 13 January 2023).

Iaacblog. (2020). Educational Programmes, Zoetic Morphologies [Online]. Available at: https://www.iaacblog.com/programs/zoetic-morphologies/ (Accessed: 21 January 2023).

Jauk, J., Vasatko, H., Gosch, L., Ingolf, C., Klaus, A., & Stavric, M. (2021). Digitai Fabrication of Growth. In Procs 26th CAADRIA Conf (Voi. 1, pp. 753-762).

Karana, E., Barati, B., Rognoli, V., & Zeeuw Van Der Laan, A. (2015). Materiai driven design (MDD): A method to design far materiai experiences. International journal of design, 9(2), 35-54.

Karana, E., Nimkulrat, N., Giaccardi, E., Niedderer, K., & Fan, J. N. (2019). Alive. Active. Adaptive: Experiential knowledge and emerging materials. International Journal of Design, 13(2), 1-5.

Rigobello, A. (2016) bioBaldaccini. Available at: https://adrienrigobello.com/biobaldaccini (Accessed: 17 October 2023).

Sheinberg, J. (2019), 'Claycelium' [Online]. Available at: https://vimeo.com/343423143?embedded=true&source=vimeo_logo&owner=91232963 (Accessed: 7 February 2023).

TEDx Talks [TEDxTalks]. (2008). 6 ways mushrooms can save the world | Paul Stamets | Available at: https://www.ted.com/talks/paul_stamets_6_ways_mushrooms_can_save_the_world/transcript (Accessed: 17 October 2023).

TEDx Talks [TEDxTalks]. (2015). ECO Coin – This is how we link Economy and Ecology| Koert Van Mensvoort | Available at: https://www.youtube.com/watch?v=wpEFu6VudLE&t=671s (Accessed: 9 October 2023).

CHAPTER 6

6.1 ON FIELD METHODOLOGY

6.2 MATERIAL INVESTIGATION

6.3 ANALYSIS OF RESULTS

... The on field investigation process unfolded across two overarching areas of focus. The first pertained to the preparatory phase of the printing process and the second related to the actual practice of sample fabrication through LDM technologies ... The material experimentation journey was methodically organized into four distinct sections: starting myco-cultures, setting up equipment and spaces, substrate testing and moulding, and eventually 3D printing alive mycelium. Upon the culmination of the field investigation phase, reflections on the obtained results paved the way for defining the project output of the thesis research work ...

Img.120

ON FIELD METHODOLOGY

6.1

6.1.1

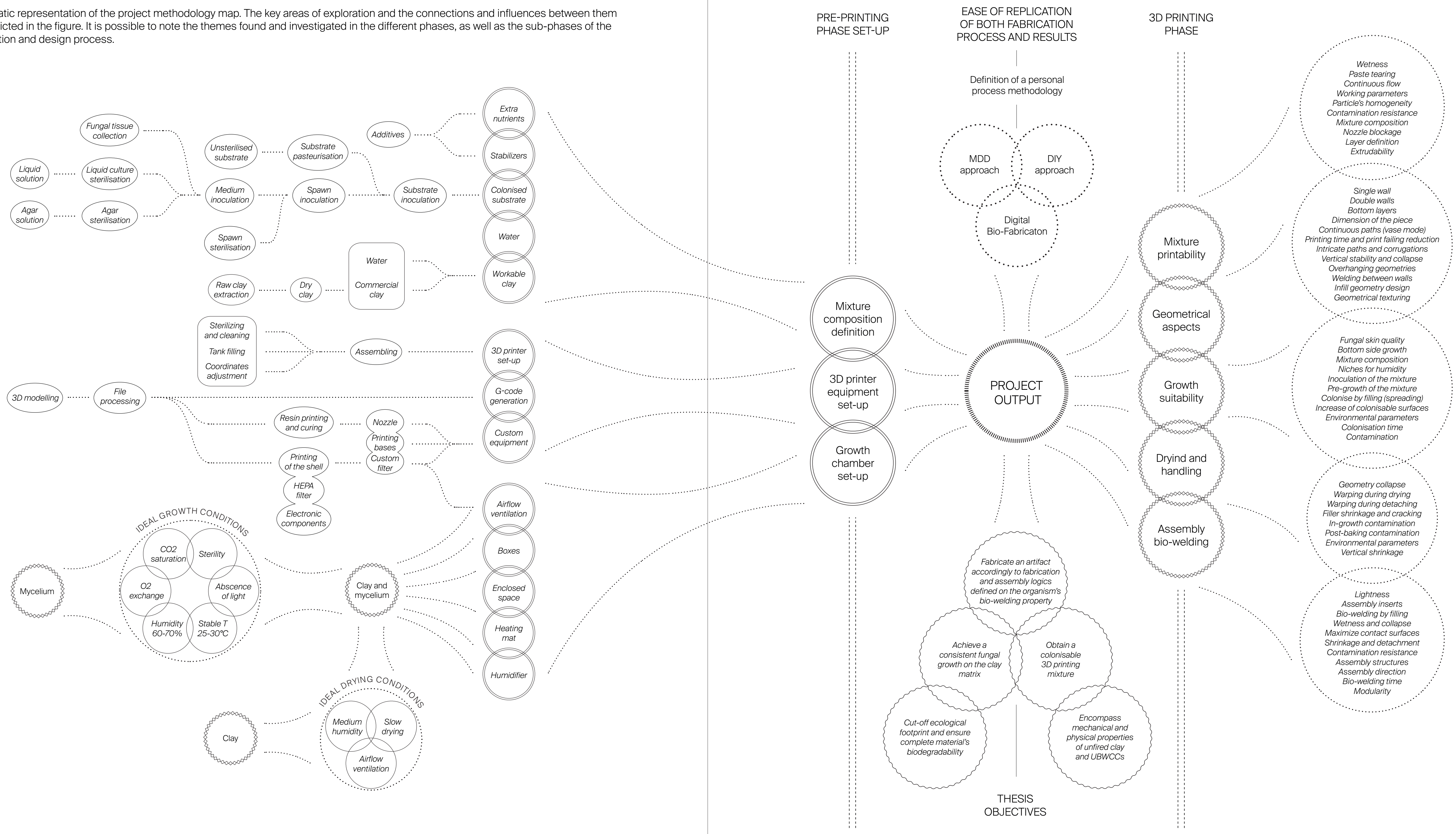
Plan of action for project implementation

The preceding chapter marked the conclusion of the theoretical exploration within the thesis, paving the way for a shift towards practical experimentation and the formulation of project outcomes. Chapter five delineated the interconnections among key aspects of the researched topics, notably converging on the intersection of two material realms: clay and mycelium. Building on insights derived from the analysis of potentialities arising from the merging of MBCs and UBWCCs, specific objectives for material experimentation were delineated, aligning with the principles of the MDD approach. Given the limited scientific knowledge on the subject, a comprehensive approach was adopted, necessitating an in-depth examination of clay and mycelium. This was imperative since the theoretical foundation couldn’t rely on existing literature, demanding an alternative method from the outset. The subsequent step involved pinpointing material-related challenges, practices, and processes, with the aim of proposing a design intervention focused on material combinations to positively impact these elements. However, the aspiration encountered difficulty due to the inherent challenges of experimenting with a hybrid material that, to some extent, does not yet exist. This material is derived from the fusion of a conventional inert substance and a living organism whose compatibility has been demonstrated only in a preliminary and approximate manner. The complexity was further heightened by the intersection of MDD with DIY and Digital Biofabrication methodologies. Despite presenting new constraints and problems, this intersection also offered opportunities, particularly in leveraging digital fabrication technologies. These technologies emerged as crucial tools not only for shaping processes and materials but also for guiding growth and fostering development during the material investigation phase.

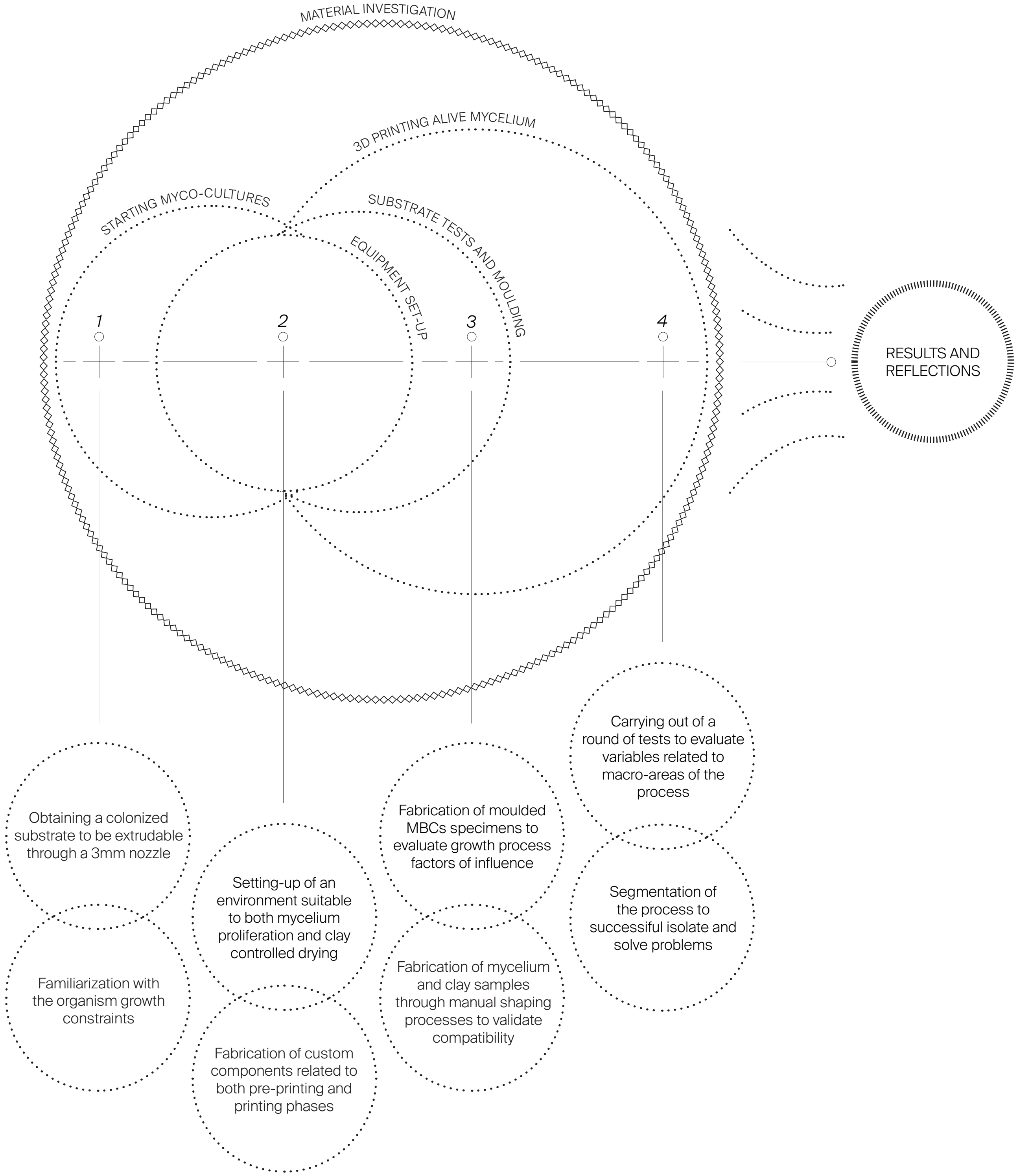
The imperative to access digital fabrication technologies, particularly the LDM additive manufacturing method, dictated that the material experimentation phase be conducted in a suitable facility. This need found fulfillment in Polifactory, the Fab Lab, and makerspace affiliated with Politecnico di Milano. These facilities not only offered the requisite tools for project realization but also harnessed the technical expertise of individuals within, notably Dr. Patrizia Bolzan, who also served as the thesis work supervisor. The designated experimentation area was compartmentalized into several spaces: a modestly sized laboratory accommodating diverse disciplines, including basic biology; rooms housing digital fabrication machinery utilized throughout the project duration; and an additional space dedicated to setting up instrumentation for initiating cultures. The primary tool employed for fabricating samples and the final prototype was the WASP 2040 printer, equipped with a WASP Extruder 3.0 LDM.

The on field investigation process unfolded across two overarching areas of focus. The first pertained to the preparatory phase of the printing process and the second related to the actual practice of sample fabrication through LDM technologies. This initial area encompassed the cultivation of fungal-based materials and the formulation of a foundational mixture composition. This involved cultivating the organism at various stages, gaining comprehensive insights into influencing factors, and creating artifacts through manual molding in MBCs and UBWCCs. Simultaneously, efforts were directed toward establishing a growth space with environmental conditions conducive to organism proliferation and post-molding arrangement of clay artifacts. This phase also witnessed the creation of custom digital-fabricated components essential for the printing and organism growth processes. The second area of investigation delved exclusively into the LDM digital fabrication process. Here, a series of experiments were conducted through sample production, aiming to explore process dynamics concerning various influencing factors. These variables encompassed both the technology and tools involved in the process and the growth aspects of the organism, leveraging bio-welding properties for the assembly of mycelium-colonized modules. The material experimentation journey was methodically organized into four distinct sections: starting myco-cultures, setting up equipment and spaces, substrate testing and moulding, and eventually 3D printing alive mycelium. Upon the culmination of the field investigation phase, reflections on the obtained results paved the way for defining the project output of the thesis research work.

Img.121
Schematic representation of the project methodology map. The key areas of exploration and the connections and influences between them are depicted in the figure. It is possible to note the themes found and investigated in the different phases, as well as the sub-phases of the exploration and design process.



Img.122
Schematic representation of the material investigation phase conducted through four different sections each one with different fields of interest and related objectives to be achieved. Despite the formal division between the areas of experimentation the material produced, equipment and knowledge acquired within the individual sections were functional in advancing the exploration by creating an overlapping of processes and results that were fundamental in shaping the final project output.



Img.123
Mycelium and clay patty sample from the third on-field investigation section during the first stages of the growth cycle.

MATERIAL INVESTIGATION

6.2

6.2.1

Starting myco-cultures

The present section of the material investigation focuses on the first process segment related to the fabrication of MBCs, focusing exclusively on the preparatory steps of cultivating the material by starting fungal cultures and subsequent inoculation of spawn and substrates. Subsequent steps related to the actual utilization of the obtained material for the purpose of making mycelium-based artifacts were addressed within the subsequent sections following the performance of further preparatory practices of the pre-printing process. Within this area of experimentation, in particular, the possibility of obtaining an inoculated substrate whose nature and composition was compatible with the constraints dictated by the available instrumentation was investigated. In this regard, the reduced particle size of the dispersed phase was a key variable to be controlled since it was decisive for proper extrusion through the nozzle during printing. At the commercial level, the set of nozzles compatible with the “LDM WASP Extruder 3.0” extruder model present on the printer and used during the field experimentation presents hole sizes of 1.5-2-3mm. Given the size of the larger nozzle and a correct dimensional relationship between it and the composition of the material to be extruded, the startup of self-grown cultures coincided with the aim of obtaining an inoculated substrate whose size of the individual particles present was thus no larger than 1.5mm. Relative to this prerogative, two types of organic substrates were therefore selected, namely hemp powder and sawdust, having individual particle sizes between 0.1-0.5mm and 0.5-1.5mm, respectively.

Despite the arrangements made during the substrate selection phase, the main issue that affected the entire first section of experimentation was related to the sizing of the grain spawn to be used to colonize the hemp and sawdust. Since this is an unavoidable intermediate step for the purpose of consistent rooting by the mycelium, it was necessary to devise a series of strategies aimed at obtaining a colonized substrate that was unconstrained by the size of the grain used to inoculate it. For this purpose, a number of methods were devised that could circumvent the exposed problem that included sieving the inoculated substrate with manual spawn removal and whipping the spawn before its use. The process of making the self-produced material was divided into a series of consequential steps: making the sealed double-entry containers for the nutrient

Img.124
Selfproduced Pleurotus Ostreatus liquid culture. A formation of filamentous spheres made of the organism’s hyphae was observed and subsequential mechanical agitation led to their dispersion within the nutrient solution made them suitable to be extracted through the use of a siringe to inoculate the grain spawn.

Img.125
Grain spawn inoculated with selfproduced Pleurotus Ostreatus liquid culture.

Img.126
Close-up of substrate contamination with the outbreak of external organisms on the hemp occurred after the inoculation strategy performed by blending and dispersing the selfproduced grain spawn.

solution, starting a liquid culture from fungal tissue, inoculating the grain spawn, and testing the different methods used to inoculate the substrate. Because of the sensitivity of the process to contaminating factors, and given the impossibility of adhering to totally sterile safety protocols within the FabLab, cultivation of a substrate made from commercially purchased spawn was also carried on in parallel with that from liquid culture. This allowed on the one hand to cut out of the process the early stages where the organism is more exposed to windows of contamination, and on the other hand to compare the quality of the results obtained on their own from scratch and those obtained from a partial base already started. The arrangements followed and the methodology applied, except for any explicated custom arrangements or strategies, are as described in the dedicated subchapter at the end of Chapter 3.

Containers produced within the self-produced substrate cultivation practice were made from glass jars whose lids were suitably modified by adding a membrane filter to allow gas exchanges and a silicone valve as access for the syringe. Starting from Pleurotus ostreatus fruiting bodies, the removal of some tissue parts was carried out, which were deposited inside a liquid nutrient solution following instrument sterilization protocols. The liquid solution in question was made according to a recipe that included a starch-rich potato boiling water base additioned with 4 percent honey. Multiple samples of the liquid solution were made with the aim of increasing the success rates of the experiment. Having made the inoculation of the nutrient solution, it was left to grow for about 25 days in which it was periodically stirred. It was noted, compared with what had previously been learned from scientific literatures, that the organism's growth time was longer before it was actually ready to inoculate spawn. Some of the solutions produced showed signs of contamination, producing black particles that settled to the bottom of the container. Others, on the other hand, successfully led to proliferation of the organism, first exhibiting filamentous spheres at the bottom, and then upon agitation and rupture formed a filamentous cloud of hyphae. The filaments formed within the solution were then used to inoculate emmer, which in the preparation stage was allowed to hydrate for an extremely prolonged period so as to allow more softening to be exploited during substrate inoculation by more easily whipping the spawn. It is not clear whether because of this factor the growth of the organism was slower either because of the high moisture content of the cereals or because the excessive softness of the material to be colonised made the organism less aggressive. Again, there was slow growth of the organism that colonized the spawn over an additional 25 days. Once the grain was ready, both hemp and sawdust were pasteurized, waiting for them to release excess water before actually proceeding with the next steps. Inoculation was carried out in percentages of 15 percent by weight of the hydrated substrates and in accordance with the first of the two strategies, that of blending the spawn and using the resulting paste to infect the hemp and sawdust. This operation was carried out with the help of a kitchen immersion blender and produced a relatively wet mixture that was dispersed within the substrates trying to shell it as much as possible and mix it with the particles homogeneously. The prepared substrates were placed inside some boxes whose lids were suitably modified through the addition of a layer of filter material that would allow gas exchanges. The growth that occurred in the indoor environment of the FabLab spaces showed signs of contamination from the days immediately following inoculation, with the proliferation of third-party filamentous organisms resulting in the failure of this strategy in all the samples produced.

Instead, the next round of tests involved the inoculation of substrate from commercially purchased grain spawn, also from Pleurotus ostreatus strain. The grain was composed of millet seeds, whose small size of about 3mm in circumference was on the one hand functional for one of the two strategies applied in this case, that of blending it, while on the other hand making the one related to its manual removal by sieving more difficult. Again, the inoculation procedure involved the both materials selected as substrates and

Img.127, 128
On the left image, fruiting bodies popping out the substrate after complete colonization of it and formation of a dense fungal incapsulating the organic matter within it. On the right the grain spawn of Pleurotus Ostreatus employed on the cultivation process.

took place following pasteurization of these and in the same weight percentages used with the self-produced grain. The first experiment involved blending the millet again with an immersion blender and dispersing it later inside the boxes with the hemp and sawdust. Keeping the same mode of growth, the same phenomenon of contamination by the same type of organisms was observed. This result suggests that the mycelium is unable to withstand the mechanical stress brought by grain fragmentation or, in any case, after being fragmented that much, is unable to win the competition with other organisms potentially still present on the substrates following pasteurization, which thus begin to proliferate in the presence of humid environments. The second strategy, on the other hand, was related to a traditional inoculation process that occurred by dispersing the millet seeds and performing stratification with the substrate particles. The inoculum rates of 15 percent and the environmental growth conditions were kept identical to the previous tests so as not to affect the final result based on this variable. However, two different solutions were used with regard to the containers in which the growth took place: in one case, the compound was placed inside plastic vacuum bags that were thermally sealed and to which a membrane filter was applied; in the other, everything was placed inside the boxes with the modified lids mentioned earlier. During growth phase, different behavior of the organism was observed depending on the two containers in which it took place. Specifically, while in the boxes a gradual expansion of hyphae from the individual seeds was started to be observed as early as the second day of growth, in the case of the bags, no beginning of growth was observed even in the following days. This is due to the deprivation of access to oxygen and the absence of gas exchange due to the walls of the vacuum bags. Therefore, this solution was immediately abandoned and cultures produced only inside the boxes were carried on. These during a period of about 20 days, exhibited progressive hyphal growth and complete colonization of both substrates leading to thickening of the fungal matrix and the establishment of a MBC within the growth box. A note regarding this method of growth is that the amount of compound in relation to the size of the boxes employed was found to be too small, with the growth of the organism being particularly concentrated on the parts in contact with the walls where there was an accumulation of carbon dioxide that promoted its more consistent develop-

Img.129
The organism's development occurs from each spawn particle and continues in all directions thus engaging organic components until their complete colonization. Therefore, it is useful to efficiently disperse the spawn within the substrate to speed up the process and make it effective.

Img.130
Close-up view of fruiting bodies emerging from the substrate after complete colonization of organic matter. Fungal formation occurs by following the direction of areas where there is a higher concentration of oxygen.

ment. This is also evidenced by the fact that on the upper surface of the substrate always in contact with oxygen, fruiting of the organism was observed in some cases. However, the influence of oxygen resulted in uneven colonization of the substrate, which presented a different colonization rate that was progressively higher as one approached the bottom of the container. However, the material obtained was found to be of acceptable quality and free of signs of contamination showing the ability to create a fungal matrix by encapsulating substrate particles within it. A portion of the substrates acquired in this phase underwent manual sieving and was employed in creating MBC samples detailed in Section 3. However, despite successfully obtaining self-produced colonized substrates, this initial experimentation phase can be considered unsuccessful in meeting the initially stated objectives. The challenge of obtaining an inoculated base with dimensions less than 1.5 mm for LDM printing proved impractical through manual sieving. This is primarily due to the randomness and excessive reliance on the human component in the sieving process. Moreover, matrix grinding would be a time-consuming practice, necessitating substrate manipulation and creating wide windows of exposure to contamination. While the first experimentation phase provided valuable insights into material growth dynamics, particularly regarding contamination and process variables, it did not yield practical solutions aligning with the research objective of printing a pre-inoculated clay mixture during the material deposition stage.

Concurrently with the self-production of substrates, there was a parallel effort to cultivate cultures by the startup Smush Materials. They collaborated in the initial phase by producing material subsequently utilized in later experimental stages related to sample production. Specifically, an inoculated substrate without grain spawn was grown by directly infecting hemp powder with fungal cultures, eliminating the intermediate step of using grain. The startup, equipped with a laboratory, maintained total control over sterilization processes through autoclaves, ensuring minimal contamination. Although the organism exhibited a slower growth rate without the presence of spawn, the final colonization rate surpassed that observed with self-produced cultures in the FabLab. The startup also combined some of this substrate with clay, creating a mixture used in an LDM-printed sample from section 4 of the on field material investigation. The purpose of this mixture, to be elaborated upon later, was to assess the impact of a pre-growth phase of the organism directly in contact with the clay matrix before printing. This approach aimed to create optimal conditions for the printed artifact to be colonized by the organism.

Img.131, 132
Progressive colonisation of the hemp substrate by using the Pleaurotus Ostreatus grain spawn commercially purchased.

Img.133, 134
In the two images the material provided by the start-up Smush materials, specifically on the left one the inoculated clay mixture with visible development of the organism on the surfaces not in contact with the plastic bag, on the right one the fungal matrix obtained from the colonization of hemp powder to create a free-spawn particle substrate suitable for printing with small nozzles.

6.2.2

Setting up equipment and spaces

The second phase of the material experimentation addressed in this section was the only one of the four to not contemplate within it any practice related to the cultivation of the organism itself, but rather focused on the preparation and setting of the equipment of the spaces and tools necessary for its realization. Specifically, within this subchapter are illustrated processes of setup of the growth chamber and the realization of some custom components manufactured specifically in view of the following steps of the field investigation through a process of hacking the growth space and digital fabrication tools. This practice led to the design of a nozzle and an air filter component to be applied to the printer and grow box respectively.

Regarding the design of the custom nozzle, some reflections were made in the previous section about the need to ensure a correct dimensional relationship between its dimensions and those of the dispersed phase particles to be extruded. The first phase of cultivation was in function of this, oriented immediately to obtain a substrate that was free of the spawn grain used to inoculate it. Considering the instrumentation available within the FabLab this meant using substrates smaller than 1.5mm that could flow smoothly through a 3mm nozzle and required the ideation of alternative inoculum strategies compared to the traditional use of grain. Given the discouraging outcomes observed in the experiments, a decision was made to shift the project intervention focus away from the intricacies of cultivating the organism, a challenging task due to the unpredictable nature of living materials. Instead, emphasis was placed on the machinery involved in the process. To achieve this, a specially designed nozzle was created with an attachment system for the printer's extruder. This solution offered flexibility by enabling the interchangeability of nozzles of varying sizes, depending on the particle size for extrusion. Specifically, the designed object aimed to facilitate the interchangeability of a set of sac-a-poche extruders accommodating particles up to 8mm in size. This effectively tripled the size of the previously printable dispersed phase, eliminating the need for spawn-free cultures. The connection to the machine followed a straightforward logic, resembling the existing nozzle but incorporating a threaded mechanism. This threaded attachment secured the nozzle element between the first and second pieces, connected to each other through a thread. To grip the steel spout

Img.135
A growth chamber was set up to position the samples in an environment with predefined conditions favourable to organism proliferation and the proper drying of the clay matrix. This space allowed control over parameters such as temperature, humidity, clean air ventilation, carbon dioxide saturation, absence of light, and sterility.

Img.136
3D printed resin components of the designed custom nozzle suitable to operate with sac-a-poche nozzles of various dimensions. Comparison with the standard nozzle from WASP Extruder 3.0 LDM of 3mm diameter, opposed to the 5mm and 8mm nozzles from the custom one.

securely, dedicated parts were custom-modeled onto the extruder's base and then manufactured using resin printing. Following this, a crucial step involved curing the material to meet the printer's working pressure parameters before it could be effectively utilized. This component's realization marked a pivotal breakthrough, resolving an issue that, as highlighted in the preceding section, had the potential to impact various aspects of the process, both upstream and downstream, initially appearing unrelated. In this sense, the project intervention was aimed at devising a solution that would place the digital fabrication tools at the service of the organism and that would make it possible for them to guide its growth.

Regarding the arrangement of the growth chamber, it entailed creating a dedicated space that could provide optimal conditions for mycelium proliferation, proper drying of the pieces, and controlled withdrawal.As for the arrangement of the growth chamber, this has involved the creation of a dedicated space that could combine ideal conditions both to allow the proliferation of mycelium and a proper drying of the pieces and a controlled withdrawal. In this regard, some reasoning has been made on the parameters on which it was possible to intervene and we proceeded to intersect the needs of the organism to the measures to be carried out when working produce clay artifacts as evidenced in the sub-chapter 2.4.2. The requirements to be met for the creation of the growth chamber were therefore as follows: control of humidity and temperature, creation of a closed space to ensure absence of light, reduction of the risk of contamination and accumulation of carbon dioxide and finally a change of clean air without this entailing each time the opening of the growth environment influencing the other variables mentioned. It was therefore decided to use a Mars Hydro grow box already at Polifactory inside which two shelves were placed, a heating mat for terrariums and a humidifier. To allow a partial control of the contamination and the accumulation of carbon dioxide, it was decided to store the artifacts inside plastic boxes during the growth cycles of the organism, which lids were modified with layers of filtering

Img.137
Custom nozzle assembled on the WASP Extruder 3.0 LDM through a traded feature to ensure proper connection under the working pressure conditions of the material deposition process.

material to allow at the same time the gas exchange with the internal environment. With regard to ensuring clean air flows without the need to open the growth tent, it was decided to use the same strategy applied with the realization of the nozzle, thus manufacturing an element that could be applied to the growth space as required. As mentioned earlier, this coincided with the development of an air filtration system utilizing a HEPA filter. This custom-designed apparatus included two FDM-printed components, within which the filter could be inserted. Two computer fans were mounted on the back of these components, enabling the intake of external air, its filtration through the HEPA filter, and the release of clean air into the growth chamber. Positioned on the side of the grow box, where there was already an access point covered by a mesh, this system played a crucial role in preparing the growth space. This step was essential for controlling vital parameters crucial to the organism's proliferation, ultimately establishing the groundwork for the subsequent phase of material experimentation, which centered on the creation of artifacts using mycelium.

^ Img.138, 139
The filtering system applied to the growth chamber was realized through FDM additive technologies and involved the use of an HEPA filter. The filter is placed inside two components that are later tightened together and on the back of which two computer fans are installed. The fans push external air through the filter membranes, ensuring the sterility of the air streams fed into the growth space.

6.2.3
Substrate tests and moulding

The third area of material experimentation conducted during the research work was devoted to understanding the behavior of the organism with the process variables of the practice of molding mycelium-based composites. The desire to focus on this area of interest before interfacing with 3D printing processes involving the organism was motivated by the novelty that MBCs fabrication processes constituted from a practical point of view for the author of the present research. The molding experiments yielded several samples, each dedicated to investigating various aspects of the growth process. These areas included the influence of the fungal strain, factors affecting the growth rate, overall composite qualities, the impact of the mould material, the composition of the hybrid mixture containing clay and mycelium, and an evaluation of the bio-welding property. Particularly, the clay and mycelium-based sample experiments aimed to validate specific thesis objectives by observing the organism's ability to spread within the substrate and colonize the clay matrix. In addition, the desire to assess the quality of the outputs from variables such as fungal strain and nature of the dispersed phase led the round of experiments to involve, in addition to the material produced by the author and presented during the first area of experimentation, substrates already inoculated and marketed for DIY production of mycelium products. A comparison was made between these substrates and the self-produced one, underscoring the limitations of the latter in contrast to the particles already inoculated with an organism engineered to achieve optimal MBC performance rather than fruiting phase optimization. To be specific, the GIY Kit from GROWN bio and the Hedel composite from Kineco.bio, two Dutch companies, were examined. The former comprised hemp particles ranging from 5 to 20mm, inoculated with Pleurotus Ostreatus through Ecovative technology. The latter consisted of sawdust particles, sized 1 to 3mm, inoculated with Ganoderma Lucidum following the protocols of Mycelium Materials Europe, a company partnered with Kineco.bio.

The experimental cycle took place at two different workspaces and periods. The initial test, focusing on fabricating the samples from the GROWN bio substrate, occurred in Barcelona under domestic environment, with partially controlled growth conditions at 26°C temperature and 40-60% humidity. The subsequent experiments, involving samples from the self-produced substrate and Hedel composite, were conducted at Polifactory under controlled conditions (80% humidity, 25°C temperature) using a customized growth chamber. All substrates involved in the exploration, except for the self-made one, were supplemented with 3 percent flour by dispersed phase weight. The clay, hydrated to 5 percent, underwent sterilization through a 60-minute boiling water bath before usage. Patties were formed by mixing substrate/clay/water in various methods and proportions, resulting in 70-100mm diameter discs, approximately 10mm in height. Ethanol was utilized to maintain sterility by cleaning surfaces before coming into contact with the substrate and clay.

Through 3D printing FDM, three 120mmx120mmx20mm molds were fabricated for producing traditional MBCs comprising only substrate and flour. The three molds were made of different materials: PTU with a 2mm thickness, PLA with a 1.2mm thickness, and BVOH with a 1.2mm thickness. The mycelium growth occurred under various modes and timing, as detailed in the subsequent specimen sheets. During the growth phase, the impact of wrapping or not wrapping the molds with plastic film to promote organism proliferation was examined. The PTU and PLA molds were reused for molding multiple samples, while the BVOH mold exclusively contributed to the creation of "MBC tile sample 3," taking part to the baking process. Additional molds involved in the crafting of traditional MBC artifacts included bowls, plates, and cups of various sizes and materials. These samples were left to grow in a plastic tray sealed within a plastic bag, alongside clay patties. The bag was punctured after a few days due to the poor gas exchange established between the organism and environment manifested through slow growth compared to the individually coated tiles. Samples were thus fabricated by filling the molds, occasionally removed or inverted, to promote consistent surface growth. The subsequent specimen sheets provide data on composition, growth conditions, objectives, and concluding considerations from each of the experiments.

Img.140
MBC tile sample 1.

OBJECTIVES AND REFLECTIONS
The sample was made to test the influence of the mould walls on the formation of a homogeneous outer skin. Specifically, this sample was compared with the following sample, and parameters such as the visibility of the hemp particles, the whiteness of the fungal matrix, and the stiffness of the composite were evaluated. The sample was taken out of the mold on the fifth day of growth, turned upside down and covered again with the plastic film to promote gas exchange with the face previously facing the mold walls. Over the subsequent two days, a denser outer skin formation was noted, attributable to direct air exposure, leading to a heightened growth rate. Growth was halted simultaneously with the control sample, and the disparity in texture color between the two specimens diminished post-baking. It is reasonable to assume that with prolonged growth periods, this discrepancy would have been more pronounced.

COMPOSITION
Pleurotus Ostreatus mycelium, GROW bio hemp substrate (5-20mm particle size), flour (3% of substrate's weight)

GROWTH CONDITIONS
Mould: 3D printed TPU
Growth period: 5 days in-mould + 2 days no-mould growth wrapped in plastic film
Average environmental temperature and humidity: 26°C, 60%
Deactivation: dried at 90°C for 2 hrs

Img.141
MBC tile sample 2.

OBJECTIVES AND REFLECTIONS
The investigation of the objectives related to this sample falls within those stated in the test involving the "MBC tile sample 1," with the intention of analyzing the matrix quality of a composite not extracted from the mold throughout the whole growth period. Notably, the surface of the tile that was in contact with the mold remained shielded from air until the baking process. No particular differences in matrix development were noted between the back and front of the sample, to the point of being essentially unnoticeable after deactivation of the organism. In both compared samples, layers of the mold were visible on the surface, indicating the mycelium's strong adhesion to the walls and precise replication of their characteristics. Sample 2 experienced less volume shrinkage during baking than sample 1.

COMPOSITION
Pleurotus Ostreatus mycelium, GROWN bio hemp substrate (5-20mm particle size), flour (3% of substrate's weight)

GROWTH CONDITIONS
Mould: 3D printed ABS
Growth period: 7 days in-mould growth wrapped in plastic film
Average environmental temperature and humidity: 26°C, 60%
Deactivation: dried at 90°C for 2 hrs

Img.142
MBC tile sample 3.

OBJECTIVES AND REFLECTIONS

The objective of the experiment was to assess the mycelium's capacity to attack and consume the BVOH mold, a water-soluble vinyl alcohol copolymer utilized as support material in 3D printing procedures. To achieve this, the mold was immersed in water beforehand to facilitate material softening and moisture retention. Upon completion of the growth process, it became evident that the organism had grown along the external walls of the mold, originating from within or from individual hemp particles that had remained attached to the walls during the filling stage. Positioned in the oven with the substrate facing downward, the mold partially melted during heating, subsequently adhering to the composite before solidifying. This led to fusion between the composite and the mold, creating a permanent scaffold to support the material. It is possible to observe a non-homogeneous texture due to contamination of the composite which occurred during the growth phase with a consequent degradation of the fungal matrix.

COMPOSITION

Pleurotus Ostreatus mycelium, GROWN bio hemp substrate (5-20mm particle size), flour (3% of substrate's weight)

GROWTH CONDITIONS

Mould: 3D printed BVOH soaked in water before filling
Growth period: 15 days in-mould growth wrapped in plastic film
Average environmental temperature and humidity: 26°C, 60%
Deactivation: dried at 120°C for 2 hrs

Img.143
MBC tile sample 4.

OBJECTIVES AND REFLECTIONS

The specimen was created by reusing the substrate from "MBC bowl sample 2," which initially exhibited slow and irregular growth due to the shape of the initial mold. The hemp was fragmented once more and placed in the new mold to test a hypothetical difference in the organism's growth rate starting from a substrate with an already initiated colonization. In addition, it was intended to test the ability of the mycelium to withstand a larger time window of contamination due to a second handling of the substrate after being subjected to environmental conditions that have in the meantime hindered its growth. The experiment showed a higher growth rate, with the organism able to fill the mold in less time and develop a thicker layer of mycelial skin. However, the specimen exhibits a different texture between the front and back due to contamination of the material and partial degradation of the composite.

COMPOSITION

Pleurotus Ostreatus mycelium, GROWN bio hemp substrate (5-20mm particle size), flour (3% of substrate's weight)

GROWTH CONDITIONS

Moulds: ceramic mug, 3D printed TPU
Growth period: 7 days first in-mould growth wrapped in plastic bag, 3 days second in-mould growth + 2 days no-mould growth wrapped in plastic film
Average environmental temperature and humidity: 26°C, 60%
Deactivation: dried at 90°C for 2 hrs

^ Img.144
MBC tile sample 5.

OBJECTIVES AND REFLECTIONS
The primary aim of the experiment was to compare the composite quality derived from the Kineco.bio substrate with that from GROWN.bio. This was achieved maintaining the same growth timing and mode as in “MBC tile sample 1”. However, the environmental conditions were slightly different because of the different spaces where the two experiments were conducted, but they are not thought to have had a decisive influence on the results. The key variables altered from the previous sample encompassed the substrate nature, particle dimensions, and the specific fungal strain utilized. Upon the culmination of the growth phase, the emergence of a denser mycelial layer was observed, attributable in part to the uniform surface progression of the matrix and partly to the reduced size of the starting substrate. Additionally, discernible color alterations resembling marble-like appeareance were visible, indicative of the fruiting process characteristic of the specific fungal strain.

COMPOSITION
Ganoderma Lucidum mycelium, Kineco.bio sawdust substrate (0.5-3mm particle size), flour (3% of substrate’s weight)

GROWTH CONDITIONS
Mould: 3D printed TPU
Growth period: 5 days in-mould + 2 days no-mould growth wrapped in plastic film
Average environmental temperature and humidity: 25°C, 80%
Deactivation: dried at 100°C for 1hr 30mins

^ Img.145
MBC tile sample 6.

OBJECTIVES AND REFLECTIONS
The sample’s purpose was to examine how the deactivation method affected the preservation of the qualities developed by the fungal matrix during the growth phase. Consequently, both the substrate utilized and the growth settings were replicated from those employed in “MBC tile sample 5.” Notably, organism deactivation occurred under atmospheric conditions, bypassing temperature-related methods. The composite was extracted from the mold on the seventh day of growth, depriving the mycelium of the necessary environmental conditions for further proliferation. A comparison between the two samples revealed a noticeable alteration in the matrix color, with the second sample displaying a yellowing effect due to exposure to suboptimal conditions. Additionally, this sample exhibited reduced composite shrinkage, retaining a volume more closely aligned with that of the mold. Sample 6 also demonstrated diminished rigidity alongside a softness loss of the surface layer.

COMPOSITION
Ganoderma Lucidum mycelium, Kineco.bio sawdust substrate (0.5-3mm particle size), flour (3% of substrate’s weight)

GROWTH CONDITIONS
Mould: 3D printed TPU
Growth period: 5 days in-mould + 2 days no-mould growth wrapped in plastic film
Average environmental temperature and humidity: 25°C, 80%
Deactivation: dried under atmospheric conditions

Img.146
MBC tile sample 7.

OBJECTIVES AND REFLECTIONS
The specific sample was fabricated using the hemp powder inoculated by the author of the current research. The substrate, previously colonized using grain spawn from Funghi Espresso, was fragmented and sifted to eliminate the seeds before being introduced into the mold, resulting in a composite comprising the fungal matrix and a singular dispersed phase. Left to cultivate for seven days, the sample was subsequently extracted from the mold and deactivated under atmospheric conditions. Notably, upon removal from the mold, the specimen showcased minimal growth on the non-mould contact surface, which gradually occurred during the period between removal and the actual deactivation of the organism. Overall, the specimen demonstrated irregular growth and notably low stiffness, primarily influenced by the inadequate filling of interstitial spaces between the particles by the fungal matrix.

COMPOSITION
Pleurotus Ostreatus mycelium, self-produced hemp substrate (0.2-1 mm particle size)

GROWTH CONDITIONS
Mould: 3D printed TPU
Growth period: 7 days in-mould growth wrapped in plastic film
Average environmental temperature and humidity: 25°C, 80%
Deactivation: dried under atmospheric conditions

Img.147
MBC tile sample 7.

Img.148
MBC tile sample 8.

OBJECTIVES AND REFLECTIONS
The objective of this experiment was to test to what extent carbon dioxide accumulation was a determining factor in the growth of the organism. Placed inside a growth chamber where the oxygen concentration was far below atmospheric levels anyway, the mould containing the substrate was not covered with plastic film as was the case with the other samples. By the end of the fifth day, no discernible growth was observed, prompting the removal of the sample from the growth environment and relocation to atmospheric conditions. Notably, upon extraction of the mold from the growth chamber, complete desiccation of the substrate became apparent, as confirmed from the detachment from the walls due to dehydration. Thus, it can be concluded that the establishment of an enclosed space is crucial to facilitate carbon dioxide saturation and maintain the necessary moisture levels for the organism's proliferation.

COMPOSITION
Ganoderma Lucidum mycelium, Kineco.bio sawdust substrate (0.5-3mm particle size), flour (3% of substrate's weight)

GROWTH CONDITIONS
Mould: 3D printed ABS
Growth period: 5 days in-mould growth no wrapping
Average environmental temperature and humidity: 25°C, 80%
Deactivation: dried aunder atmospheric conditions

Img.149
MBC bowl sample 1.

OBJECTIVES AND REFLECTIONS
The objective of the experiment was to assess the organism's capacity to digest the substrate and produce thicker artifacts within the same timeframe as that used for generating thinner samples, like tiles. The thickness-growth time ratio was decisive in this regard, with the result of the experiment showing minor development of hyphae and the formation of a frail, non-cohesive fungal matrix of bound substrate particles. A stainless steel bowl, measuring 12cm in diameter and 6cm in depth, served as the mold for the experiment. It is hypothesized that the nature of the mold material did not influence the slow growth of the mycelium, which is reasonably attributable only to the thickness of the artifact and the lower gas exchange it established between the organism and its surroundings.

COMPOSITION
Pleurotus Ostreatus mycelium, GROWN bio hemp substrate (5-20mm particle size), flour (3% of substrate's weight)

GROWTH CONDITIONS
Mould: stainless steel bowl
Growth period: 5 days in-mould growth wrapped in plastic bag
Average environmental temperature and humidity: 26°C, 60%
Deactivation: dried at 90°C for 2 hrs

Img.150
MBC bowl sample 2.

OBJECTIVES AND REFLECTIONS
The aim of the experiment was to examine the efficacy of employing a combination of a mold and a counter mold to create a geometric structure featuring an internal cavity. Initially, the substrate was placed within a ceramic cup, and subsequently, a vertical plastic cylinder was introduced to facilitate gradual filling up to the rim. The density of particle compaction, crucial for their adherence to the walls, along with the approximately 10 cm depth of the combined mold fabricated affected the amount of oxygen made accessible to the organism. Notably, as the initial growth progressed and the plastic counter mold was removed to enhance the surface finish, a gradual deterioration in the quality of the matrix towards the base was observed. The bottom part of the sample was thus fragmented and employed in the making of the "MBC tile sample 4."

COMPOSITION
Pleurotus Ostreatus mycelium, GROWN bio hemp substrate (5-20mm particle size), flour (3% of substrate's weight)

GROWTH CONDITIONS
Mould: ceramic mug
Growth period: 7 days in-mould growth wrapped in plastic bag
Average environmental temperature and humidity: 26°C, 60%
Deactivation: dried at 90°C for 2 hrs

Img.151
MBC bowl sample 3.

OBJECTIVES AND REFLECTIONS
The creation of the sample involved filling a ceramic bowl with the inoculated substrate. The experiment, initially lacking specific objectives, aimed to familiarize with the mycelium and attempt the replication of relatively simple shapes. However, the use of a concave mold posed challenges in maintaining uniform thickness and smooth surfaces without the aid of a counter mold. The irregularities on the inner walls of the bowl were notably influenced by the dispersed phase's composition, comprising particles of highly variable sizes. A notable distinction emerged between the surfaces of the artifacts grown in contact with the mold, exhibiting a polished finish due to applied pressure, and those developed without wall contact. Consequently, the experiment prompted speculation about the necessity of a counter mold to achieve surface uniformity in the MBC artifacts.

COMPOSITION
Pleurotus Ostreatus mycelium, GROWN bio hemp substrate (5-20mm particle size), flour (3% of substrate's weight)

GROWTH CONDITIONS
Mould: ceramic bowl
Growth period: 7 days in-mould + 7 days no-mould growth wrapped in plastic bag
Average environmental temperature and humidity: 26°C, 60%
Deactivation: dried at 90°C for 2 hrs

Img.152
MBC bowl sample 4.

OBJECTIVES AND REFLECTIONS
This sample follows the considerations of the previous one and was made by filling a ceramic plate with the inoculated substrate.The experiment, initially lacking specific objectives, aimed to familiarize with the mycelium and attempt the replication of relatively simple shapes. However, the use of a concave mold posed challenges in maintaining uniform thickness and smooth surfaces without the aid of a counter mold. The irregularities on the inner walls of the container were notably influenced by the dispersed phase's composition, comprising particles of highly variable sizes. A notable distinction emerged between the surfaces of the artifacts grown in contact with the mold, exhibiting a polished finish due to applied pressure, and those developed without wall contact. Consequently, the experiment prompted speculation about the necessity of a counter mold to achieve surface uniformity in the MBC artifacts.

COMPOSITION
Pleurotus Ostreatus mycelium, GROWN bio hemp substrate (5-20mm particle size), flour (3% of substrate's weight)

GROWTH CONDITIONS
Mould: ceramic plate
Growth period: 7 days in-mould + 7 days no-mould growth wrapped in plastic bag
Average environmental temperature and humidity: 26°C, 60%
Deactivation: dried at 90°C for 2 hrs

Img.153
Mycelium and clay patty 1.

OBJECTIVES AND REFLECTIONS
This particular sample was prepared to enable the observation and comparison of potential disparities in organism growth between two samples. These samples were composed of identical proportions of clay and substrate but differed in the presence or absence of an additionale outer layer of substrate. Specifically, sample 1 was manually molded, ensuring that the outer surfaces remained free of dispersed particles. Consequently, the organism's diffusion into the clay took place solely from the inner dispersed phase within the clay matrix. Upon the conclusion of the growth phase, a consistent organism expansion and complete colonization of the sample were noted, resulting in the development of a thick fungal layer. Notably, this layer exhibited remarkable resilience, particularly before the deactivation phase, allowing the sample to be handled without any compromise to the integrity of the fungal matrix. Sample's surface damaged during transportation.

COMPOSITION
Pleurotus Ostreatus mycelium, 40% GROWN bio hemp substrate (5-20mm particle size) + flour (3% of substrate's weight), 60% red clay

GROWTH CONDITIONS
Mould: manual shaping
Growth period: 14 days growth wrapped in plastic bag
Average environmental temperature and humidity: 26°C, 60%
Deactivation: dried at 90°C for 2 hrs

Img.154
Mycelium and clay patty 2.

OBJECTIVES AND REFLECTIONS
Sample 2 was produced as part of an experiment aiming to examine the impact of an extra outer layer of substrate on the organism's colonization rate. Similar to sample 1, it was created using the same clay-substrate proportions, but it entailed the application of a coating comprising the dispersed phase, which adhered to the outer surfaces. After the growth phase, complete colonization and the formation of a substantial fungal layer were observed, although it appeared more irregular than in sample 1 due to the non-homogeneous surface of the sample. In terms of growth speed, sample 2 exhibited a slightly faster development compared to its counterpart lacking the additional layer. This difference was attributed to the organism's enhanced ability to break free from the clay matrix and establish itself on the surface, facilitated by the added layer. No other notable distinctions were identified between the two samples. Sample's surface damaged during transportation.

COMPOSITION
Pleurotus Ostreatus mycelium, 40% GROWN bio hemp substrate (5-20mm particle size) + flour (3% of substrate's weight), 60% red clay, additional outer layer of substrate after shaping

GROWTH CONDITIONS
Mould: manual shaping
Growth period: 14 days growth wrapped in plastic bag
Average environmental temperature and humidity: 26°C, 60%
Deactivation: dried at 90°C for 2 hrs

Img.155
Mycelium and clay patty 3.

OBJECTIVES AND REFLECTIONS
Similarly to the preceding experiment, the present sample and the subsequent one were produced for comparative testing, aiming to assess the impact of the supplementary layer of substrate on the organism's growth rate. In this instance, the proportions of clay and substrate were altered from the previous set of samples, while being maintained constant between the two samples under examination. Specifically, sample 3 presented an outer surfaces with no dispersed particles. Following the growth period, consistent organism expansion and complete colonization of the sample were observed, resulting in the formation of a substantial fungal layer. In contrast, irregular growth was noted on the bottom of the sample, attributable to prolonged exposure to water resulting from fungal metabolism and its accumulation at the base of the container. Nevertheless, no other distinctions were evident in terms of growth timing or the general quality between samples 3 and 1, differing solely in the percentage of clay incorporated within the mixture.

COMPOSITION
Pleurotus Ostreatus mycelium, 25% GROWN bio hemp substrate (5-20mm particle size) + flour (3% of substrate's weight), 75% red clay

GROWTH CONDITIONS
Mould: manual shaping
Growth period: 14 days growth wrapped in plastic bag
Average environmental temperature and humidity: 26°C, 60%
Deactivation: dried at 90°C for 2 hrs

Img.156
Mycelium and clay patty 4.

OBJECTIVES AND REFLECTIONS
Distinguishing itself from the preceding sample, this particular one featured the extra external substrate coating. After the growth phase, complete colonization and the formation of a significant fungal layer were evident, although a more irregular appearance was observed compared to sample 3, owing to the uneven surface due to the particles presence. In terms of growth rate, a slightly faster development than its counterpart lacking the supplementary layer was observed, attributed to the organism's enhanced ability to break free from the clay matrix and colonize the surface. No other specific differences were identified between the two compared samples, nor between sample 4 and 2, both of which incorporated the additional substrate layer varying percentages of clay. The sample was sectioned before baking to analyze the spread of mycelium within the clay matrix, which was found to be absent and suggested that the organism was only able to develop at the surface level.

COMPOSITION
Pleurotus Ostreatus mycelium, 25% GROWN bio hemp substrate (5-20mm particle size) + flour (3% of substrate's weight), 75% red clay, additional outer layer of substrate after shaping

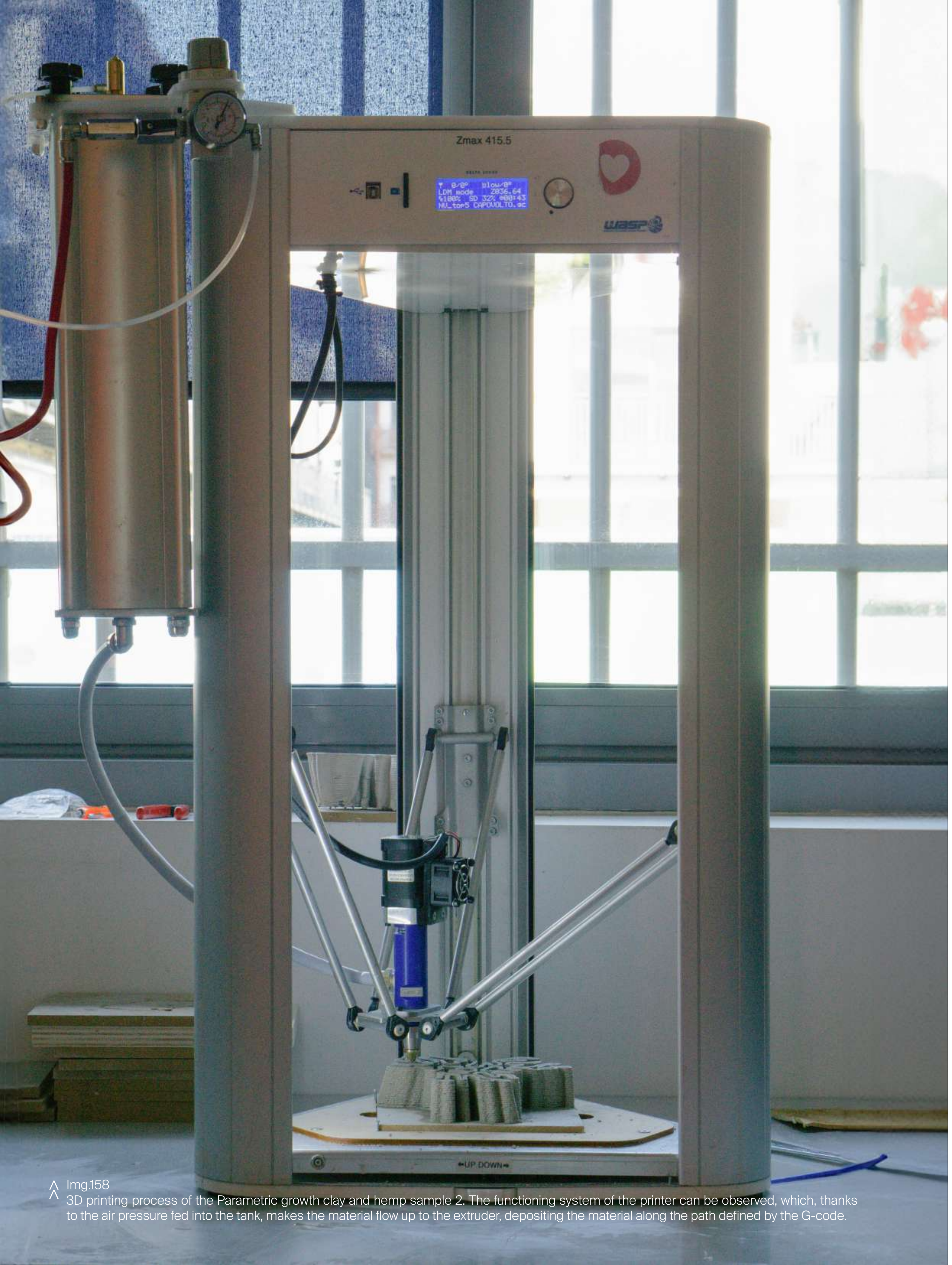
GROWTH CONDITIONS
Mould: manual shaping
Growth period: 14 days growth wrapped in plastic bag
Average environmental temperature and humidity: 26°C, 60%
Deactivation: dried at 90°C for 2 hrs

Img.157
Mycelium and clay patties 5-6.

OBJECTIVES AND REFLECTIONS
These two samples wanted to explore the biowelding potential of the organism and determine whether it could facilitate bonding between two artifacts comprising clay. As the experiment occurred during the first time interfacing with mycelium, the hypothesis of bonding couldn't be confirmed beforehand, primarily due to a limited understanding of the organism's behavior in relation to clay materials. Both samples were crafted from an identical mixture, maintaining a 1:1 ratio of clay to substrate. After ten days, the mycelium exhibited consistent growth, culminating in the formation of a robust fungal layer. Subsequently, the two pieces were brought into contact by simply placing them atop each other, without exerting any pressure, to examine capacity to join imperfectly adhered artifacts. At the end of the fourth day, the samples now fused into one, were deactivated. Baking contributed to stabilize the bond formed and proved successfully the hypotheses of the experiment.

COMPOSITION
Pleurotus Ostreatus mycelium, 50% GROWN bio hemp substrate (5-20mm particle size) + flour (3% of substrate's weight), 50% red clay

GROWTH CONDITIONS
Mould: manual shaping
Growth period: 10 days individual growth + 4 days in-contact surfaces growth wrapped in plastic bag
Average environmental temperature and humidity: 26°C, 60%
Deactivation: dried at 90°C for 2 hrs



Img.158
3D printing process of the Parametric growth clay and hemp sample 2. The functioning system of the printer can be observed, which, thanks to the air pressure fed into the tank, makes the material flow up to the extruder, depositing the material along the path defined by the G-code.

6.2.4

3D printing alive mycelium

The material investigation conducted up to this point has offered initial interesting insights regarding the behavior of the organism in relation to growth conditions and deactivation methods and has also contributed to the evaluation of the dispersed phase on the macroscopic qualities of mycelium-based materials. The experimentation carried out in the previous section, however, only focused on the practice of moulding, mainly exploring the growth processes related to the making of MBC artifacts. An initial field combination of clay and mycelium yielded interesting findings in each case, highlighting firsthand the compatibility between the clay matrix and the organism. Following the investigation conducted in the first three sections focused respectively on an initial culture phase, the setting up of the printing and growth equipment to support the process, and finally the molding phase, the ground was prepared for the last area of exploration related to the combination of LDM digital fabrication technologies and hybrid materials at the intersection of MBCs and UBWCCs.

The last area of interest saw the practice of printing being conducted with the aim of substantiating the thesis objectives stated at the end of chapter five through the analysis of the process in its entirety, from the preparation of the mixture, to the variables of modeling and file preparation, to the extrusion process itself, to the growth process up to the assembly and deactivation of the organism. The field research is concise with the accomplishment of several rounds of experiments that dealt with different aspects of the process and following which the samples fabricated were compared with each other in light of the results obtained. Although the printing process in its entirety involved multiple aspects of the practice that often intersected with each other, the definition of some specific objectives helped to direct the material investigation toward isolating the problems encountered from time to time during the fabrication of individual samples and allowed the formulation of intervention strategies aimed at their resolution in subsequent tests. Specifically, the experiments focused on five macro-areas of practice investigation that were analyzed through the use of radar charts so that the results obtained could be evaluated in a more clustered way and samples could be compared on the basis of objective criteria within isolated process segments. The areas of analysis were therefore divided into:

- Mixture printability: the considerations made within this section were aimed at defining an ideal mixture composition by analyzing its behavior in relation to the material extrusion and deposition process. To do this, parameters such as the quality of the definition of the printing layers, the ease with which the material was able to flow within the printer components and the ability not to clog the nozzle, the homogeneity of the deposited material, the visibility of aesthetic and structural defects due to the presence of dispersed phases of varying nature and size were evaluated. Moreover were analysed as well the correlation between the density of the printing mixture and issues related to flow continuity, the ease of filling the tank and the consequent formation of bubbles, the pressure required to extrude the mixture, the suitability of the consistency of the mixture in achieving certain shape objectives, and finally the influence of the degree of hydration of the deposited material within the growth and assembly phase;

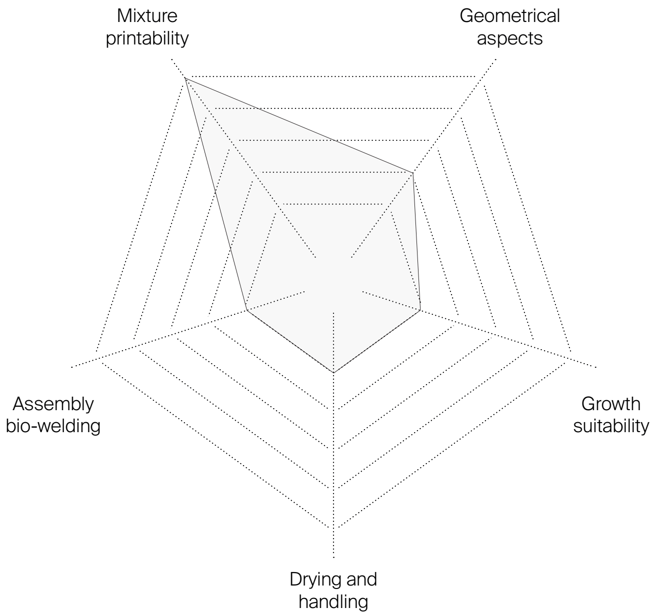
- Geometrical aspects: the analysis related to this area of interest focused on the aspects related to the construction of printed volumes and their influence not only during the mixture deposition phase, but within the process as a whole. This means that the role of geometries has been considered in ensuring the stability necessary to prevent the collapse of parts during printing and assembly, in promoting organism growth through the creation of moisture niches, the maximization of colonizable surface area and that of contact between modules, the dimensional influence of parts on the window of potential problems related to the printing process, the influence of background geometries in favoring the handling of parts and avoiding their deformation upon separation from the printing base, and finally the possibility of texturing artifact surfaces through geometric reasoning;

- Growth suitability: internal evaluations in this section dealt with aspects related to the behavior of the organism and the maximization of its growth in relation to the variables of mixture composition, geometric ones, the definition of a clay matrix inoculation methodology that contemplated non-sterile printing and a colonization by filling, the inoculation of the mixture immediately before the preparation phase of the mixture and its deposition, the influence of an intermediate growth period in the interval between the realization of the clay mixture and its deposition. Parameters such as the quality of the obtained fungal matrix, environmental growth parameters and their influence in favoring or reducing the risks of contamination by other organisms were then investigated;

- Drying and handling: in this area of analysis, on the other hand, the shrinkage behavior of the material and the ease with which artifacts could be handled at all stages of the process (molding, detachment from printing bases, assembly) were evaluated. In particular, it was observed how the mixture and the designed geometries had an influence on the drying behavior of the parts with respect to deformation, cracking, and shrinkage rate in all spatial directions;

- Assembly and bio-welding: in the last area of analysis, considerations were made on how the assembly stage and bio-welding properties of the mycelium were affected by the other four areas mentioned. In particular, the correlation with the design phase of the geometries found to be functional in maximizing contact surfaces and creating interlocking features to determine the effectiveness of joints between parts was crucial. Also, related to this area was the evaluation of some part connection strategies based on a diversification of the direction of printing and that of assembly, the implementation of external components that could prepare features for connection to other elements, and the creation of assembly structures oriented to the control of the distribution of weights and stress loads. Finally, evaluations were carried out on the bio-welding process itself conditioned by the other macro-areas and found to be decisive in the basis of the design choices adopted for the realization of the final project output.

^ Img.159
Parametric growth clay sample 1.



^ Img.160
Radar chart of the sample’s attributes.

MIXTURE COMPOSITION
Clay, water

GEOMETRY TRAITS AND MAIN QUALITIES
Single wall, continuous intricate paths, computational modelling

FILE PROCESSING DATA AND WORKING PARAMETERS
Nozzle: 3mm
Layer Height: 1.5mm
Pressure: 2-3 bar
Printing time: 2hrs

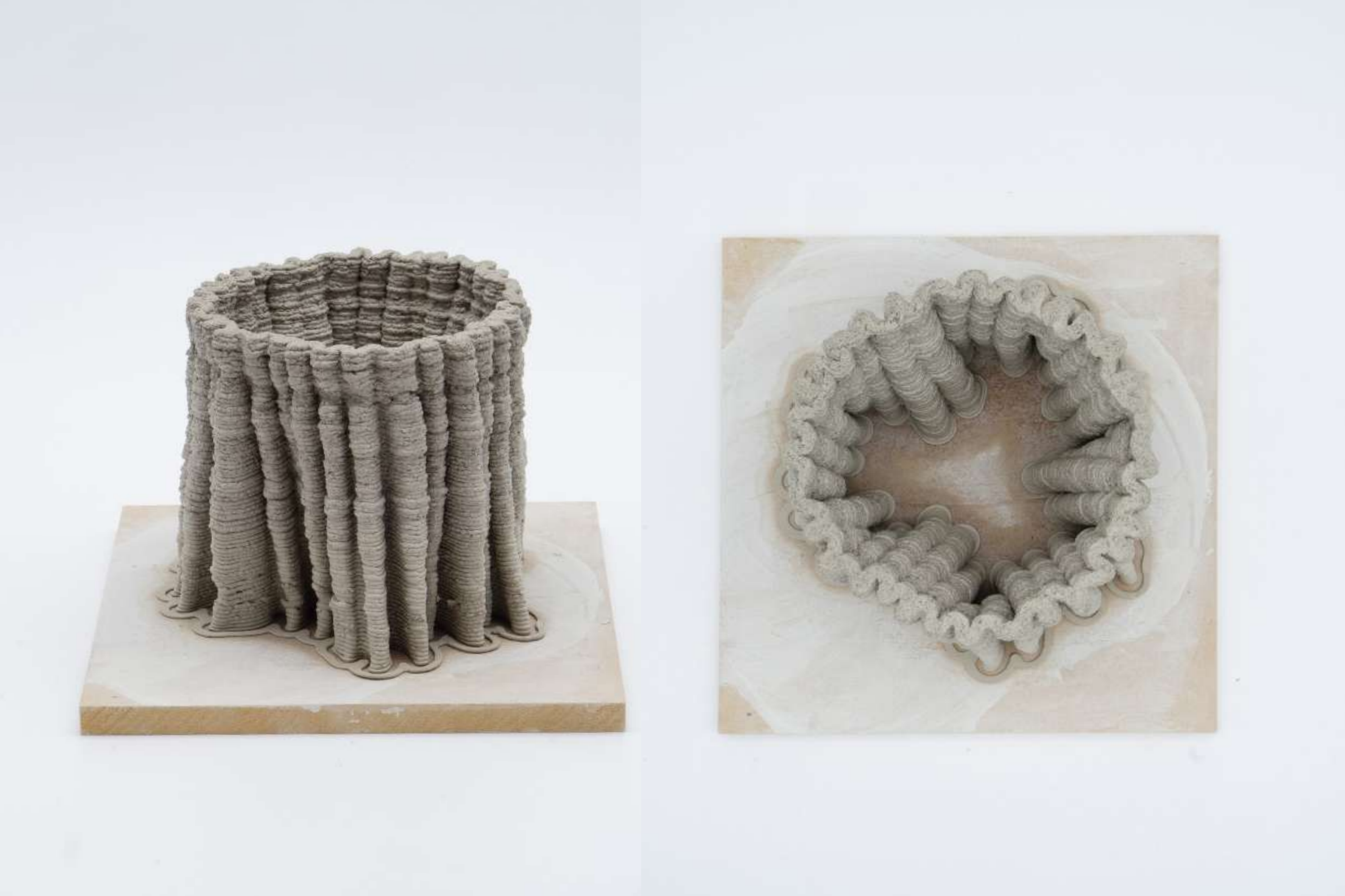
HYPOTESIS AND SUM OF OBJECTIVES
Layer definition evaluation, creation of inlets and humidity pockets, geometry stability during printing

GROWTH CONDITIONS
Growth period: none
Average environmental temperature and humidity: 22°C, 40-60%
Deactivation: none

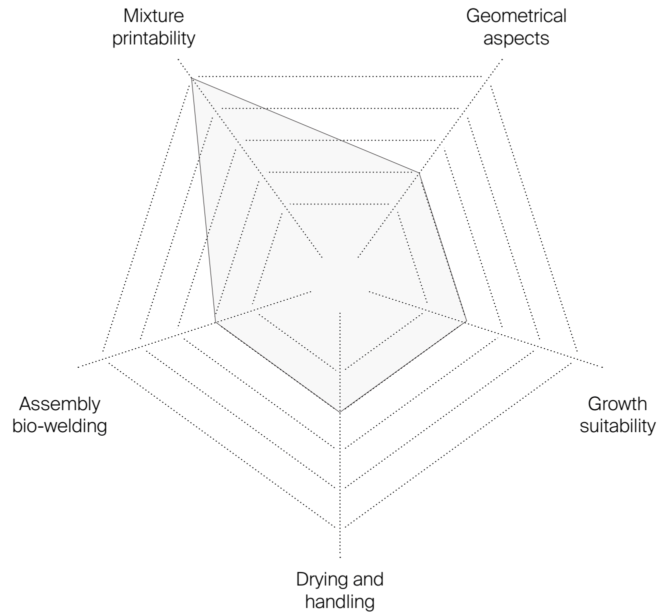
^ Img.161, 162
Details of the sample’s bottom and top printing paths generated through parametric modelling on Grasshopper..

OBJECTIVES, RESULTS AND REFLECTIONS
The sample in question was the first in chronological order to be made within the experimental phase related to 3D printing, as well as the first artifact ever made by the author via LDM. For this very reason, with the desire to familiarize with the process and to be able to observe and understand its technicalities, the first round of prints was made with a mixture containing only stoneware clay. Employing only the clay material and excluding any dispersed phase allowed for the utilization of a standard 3mm nozzle, ensuring a smooth and consistent flow with minimal printing pressure. Nonetheless, due to the absence of an organic component in the mixture, any practical attempt to facilitate colonization was naturally restricted. Instead, the focus shifted on other aspects related to the printability of such intricate geometries and their role in relation to an hypothetical inoculation of the mixture.

The artifact presents intricate single-walled geometries built through a loft from an origin curve and a target curve, both closed and continuous. Using a parametric approach in Rhino and Grasshopper, a plugin was employed to simulate an organic growth pattern, transitioning between the original paths. The decision to adopt this complex geometry was driven by the aspiration to establish a highly intricate print path that could maintain stability while remaining single-walled. This logic becomes apparent when examining the closely spaced yet detached walls at the base, designed to anticipate potential cavity filling through fungal growth. Hence, the primary aim of this experiment was twofold: first, to assess how this specific geometry influenced the stability of the artifact during the printing and drying stages, and second, to explore a modeling approach combining computational and natural growth models to predict and incorporate organism behavior. During the printing process, the vertical development facilitated the compactness of the structure and the creation of moisture-retaining pockets, ensuring a gradual release of moisture. However, the fragility resulting from the single-wall construction required complete drying before handling and removal from the printing base, causing a vertical volume shrinkage of approximately 20 percent. Fortunately, the piece’s elasticity, achieved through an optimal blend of clay and water, prevented any collapse during this phase. Nevertheless, the realization of this specimen unveiled challenges pertaining to the modular assembly of such geometries. According to the assembly logic, modules should only be joined vertically, relying on the contact between their perimeters. This constraint, even when considering filling methods for inoculation, necessitates precise terminal path planning for junction points and careful management of the artifact’s shrinkage behavior, which remains delicate and challenging to manipulate until fully dry. The complex path intricacies and substantial material deposition per layer extended the printing duration to approximately two hours, exposing the piece to a prolonged vulnerability window for potential errors such as bubbles or interruptions in material flow. Notably, the excellent layer definition resulting from the clay’s exclusive presence amplifies the visibility of any imperfections within the mixture.



Img.163
Parametric growth clay and hemp sample 1.



Img.164
Radar chart of the sample's attributes.

MIXTURE COMPOSITION
Clay 64%, hemp powder 9,5% (0.1-0.5mm particle size), water 26,5%, self-produced hemp substrate inoculated with Pleurotus Ostreatys as a filling during the second stage of the experiment

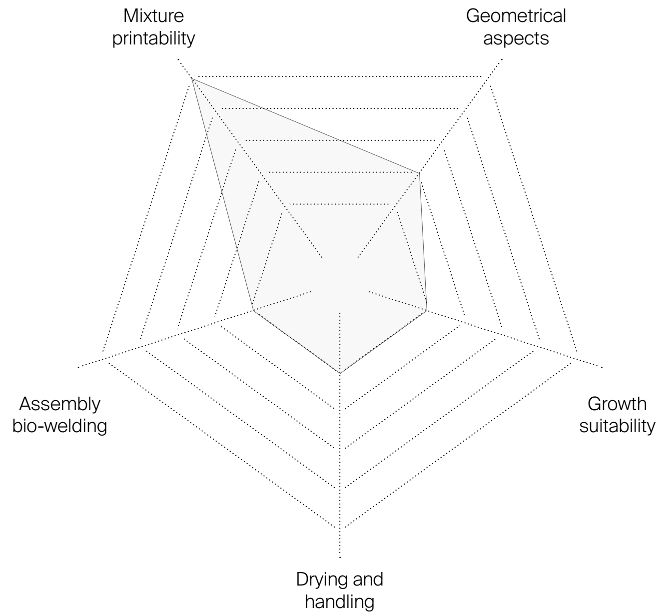
GEOMETRY TRAITS AND MAIN QUALITIES
Single wall, continuous intricate paths, computational modelling, modularity

FILE PROCESSING DATA AND WORKING PARAMETERS
Nozzle: 3mm
Layer Height: 1.5mm
Pressure: 3.5-4 bar
Printing time: 1hr 15mins

HYPOTESIS AND SUM OF OBJECTIVES
Layer definition evaluation, geometry stability during printing, effectiveness of contact surfaces, non-sterile deposition, steam sterilisation post-printing, clay's matrix inoculation by filling, inlets filling, bio-welding

GROWTH CONDITIONS
Growth period: 14 days growth placed in plastic box
Average environmental temperature and humidity: 26°C, 80%
Deactivation: dried at 120°C for 2 hrs

Img.165
Parametric growth clay and hemp sample 2.



Img.166
Radar chart of the sample's attributes.

MIXTURE COMPOSITION
Clay 64%, hemp powder 9,5% (0.1-0.5mm particle size), water 26,5%, self-produced hemp substrate inoculated with Pleurotus Ostreatys as a filling during the second stage of the experiment

GEOMETRY TRAITS AND MAIN QUALITIES
Single wall, continuous intricate paths, computational modelling, modularity

FILE PROCESSING DATA AND WORKING PARAMETERS
Nozzle: 3mm
Layer Height: 1.5mm
Pressure: 3.5-4 bar
Printing time: 2hrs

HYPOTESIS AND SUM OF OBJECTIVES
Layer definition evaluation, geometry stability during printing, effectiveness of contact surfaces, non-sterile deposition, steam sterilisation post-printing, clay's matrix inoculation by filling, inlets filling, bio-welding

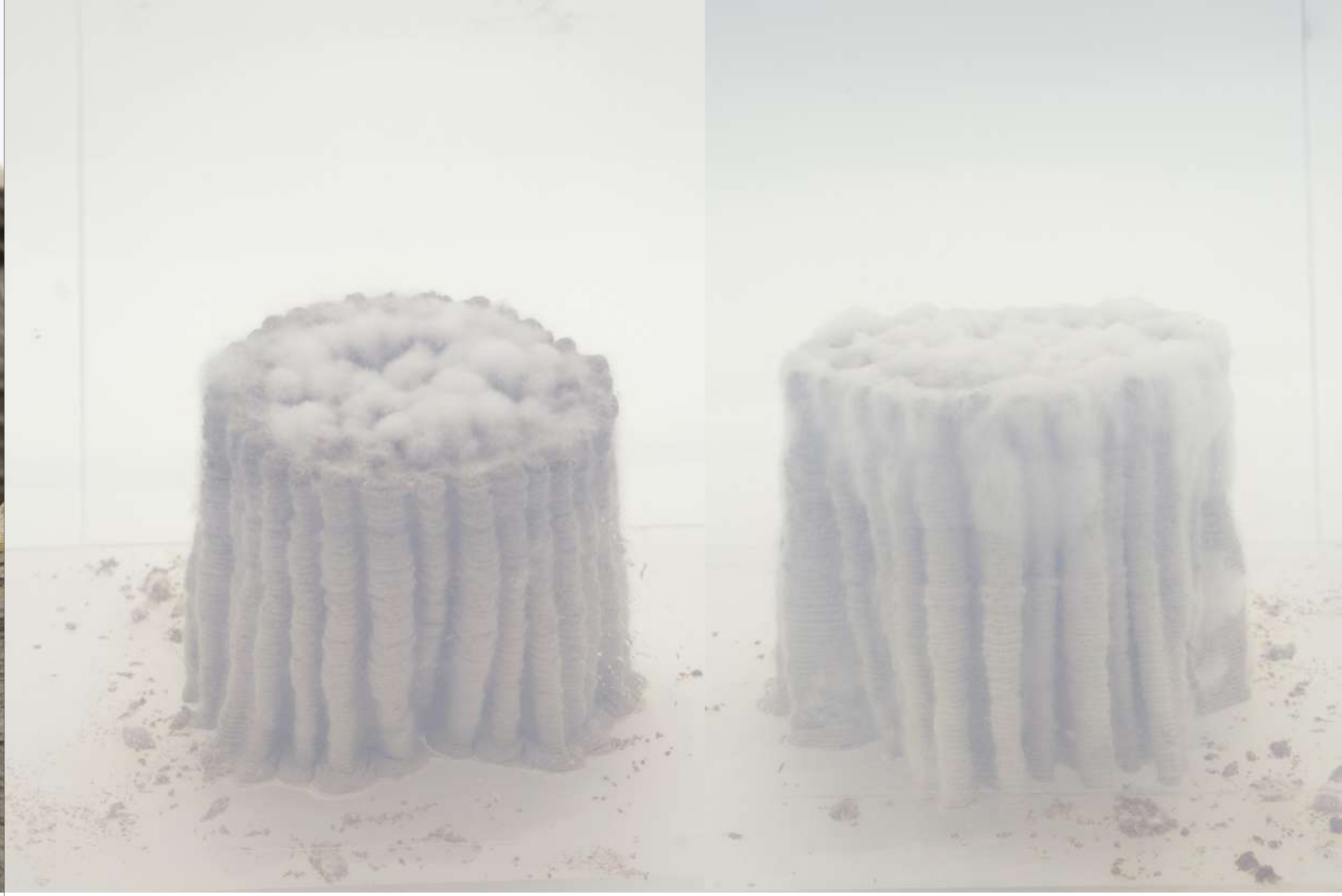
GROWTH CONDITIONS
Growth period: 14 days growth wrapped in plastic box
Average environmental temperature and humidity: 26°C, 80%
Deactivation: dried under atmospheric conditions

^ Img.167, 168
Close-up view of the contaminated areas of the samples exhibiting the development of white filaments and yellow stains.

OBJECTIVES, RESULTS AND REFLECTIONS

The second experiment in the sample list showcases a geometry created using similar modeling principles as the previous one. This artifact comprises two distinct modules, obtained by sectioning the overall volume generated via computational modeling on Grasshopper, guided by the growth pattern. The first module, the first to appear in photographic order, represents the lower part of the structure but is designed to occupy the upper section during stacking, a necessity dictated by geometric constraints. These constraints also necessitate the reverse molding of both pieces to avoid cantilever walls. Notably, the printing stage involved a mixture of clay and non-sterilized hemp powder, with the dispersed phase being small enough to allow extrusion through a standard 3mm nozzle without clogging. The hemp powder, although added to the clay and water in percentages of less than 10 percent, influenced several aspects of the behavior of the mixture throughout the process. Specifically, during the preparation of the mixture it was necessary to increase the amount of water required due to the absorption of this by the hemp, which positively affected both the flow continuity by making it porous and less dense, and the elasticity of the layers once deposited. However, the pressure required was slightly higher, standing at a maximum value of 4 bar during some printing stages. The printing times for the first module were comparatively shorter, around one hour and fifteen minutes, while the second module took approximately two hours due to its increased complexity. This finds its basis in the fact that although the machine path was again intricate, the first of the two modules was of the two the one geometrically closest to the least complex curve according to the logic of loft construction with which the overall geometry was modeled. In any case, again the length of the printing process of each of the two modules exposed them to a wide window of potential problems due to the occurrence of flow interruption due to bubbles. The less pronounced presence of recesses and indentations in favor of a more homogeneous vertical development provided the first piece with greater stability than the second. In particular, the less variability of the curves though always supported by the path corrugations, resulted in greater handling of the module in the intermediate stage of drying, with the base surface itself detaching from the printing base more quickly. In contrast, the second module, mainly for reasons related to the path geometry with a central convergence of the three macro-reentrances, was found to be extremely fragile to handle even following the drying phase. The first drying of the pieces, which took place in a controlled manner under atmospheric conditions, observed a vertical shrinkage of 30 percent, which was greater than with the clay-only mixture and due to the influence of hemp in releasing the water contained within.

Either due to having hydrated hemp without sterilizing it or due to deliberately slowing down the drying process to make it controlled, there was a beginning of fungal and mold growth on the walls of both artifacts. This contamination manifested itself in two different ways: on the upper part of the modules characterized by faster drying due to gravity, dark yellow mottling appeared, while on the lower, wetter areas and especially near the recesses, white filamentous organisms developed. From early on during this experimental phase, the issue of substrate sterilization and the ease with which the substrate could become infected during the various steps of the process became apparent, especially during mixture preparation, machine loading and material deposition exposed to large windows of potential contamination due to the duration of printing artifacts of such size and complex geometries. The contamination issue impeded the experiment's objectives, necessitating the development of a practical solution. The experiment itself revolved around three primary goals: obtaining initial insights into the printing process using a composite mixture of clay and hemp powder, assessing the feasibility of dividing geometries into smaller, interconnected modules with shared junction points, and exploring the potential colonization of the artifact using unsterilized substrate by filling cavities with colonized substrate and spreading it across the printed piece.



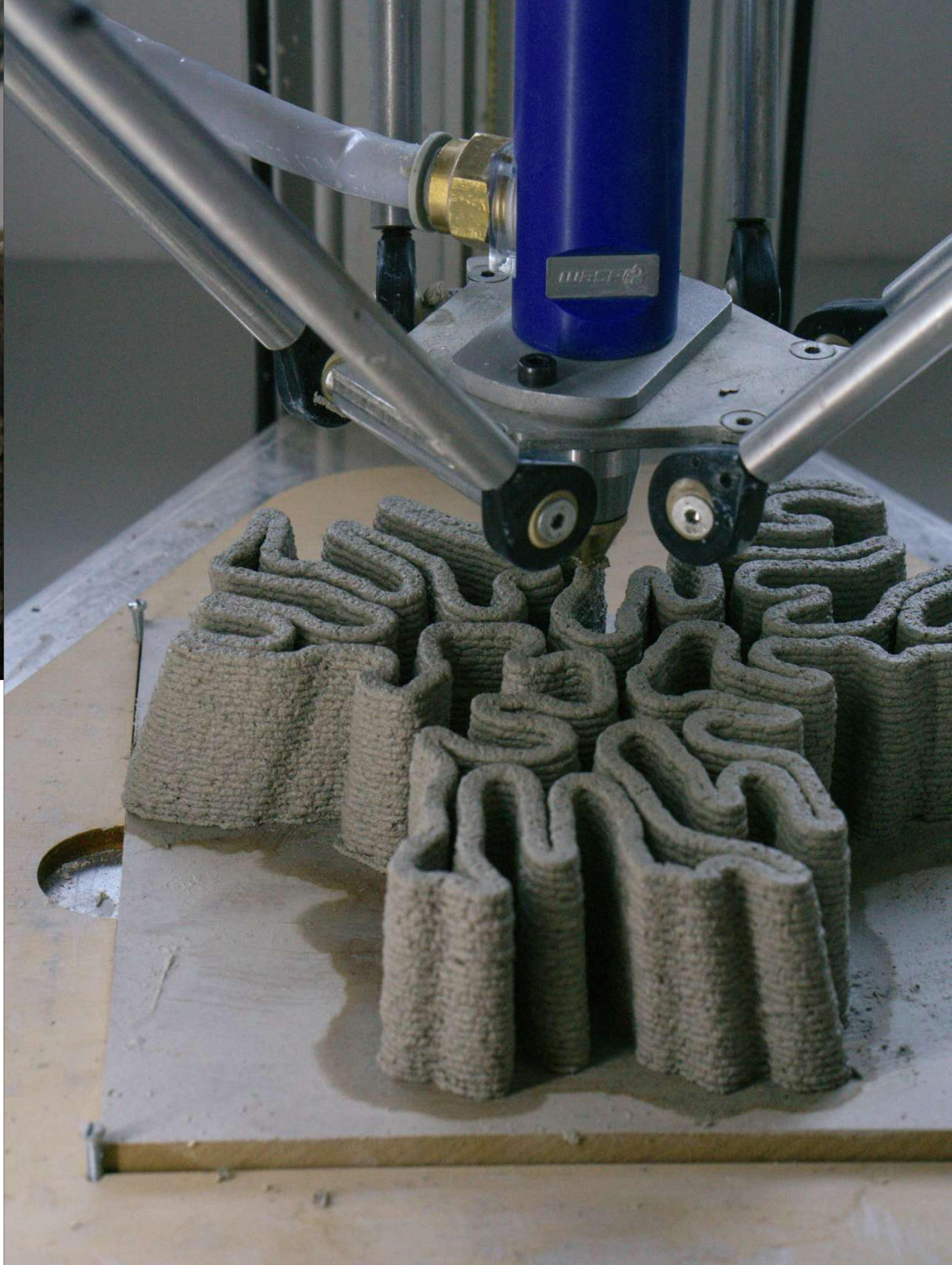
^ Img.169
Inoculation by filling of the sample with the self-produced hemp substrate, progressive spreading of the mycelium on the clay matrix.

At this point, both modules were allowed to dry completely so that, once all moisture was lost, ideal proliferation conditions for contaminants would cease to exist. Once this condition was achieved, the modules were placed inside a closed plastic box and subjected to a sterilization process that took place by prolonged exposure of the pieces to the glowing vapors of a steamer. This step had a dual purpose: to ensure that contaminating organisms were effectively eliminated and to partially rehydrate the artifact material so as to bring the humidity back within suitable parameters for mycelium colonization. Following multiple cycles of vapor input inside the boxes, the pieces were extracted and quickly filled with the homemade hemp-based substrate made from the Funghi Espresso grain spawn. This operation proved to be at the limits of feasible for the smaller module because of the difficulties in reaching the narrower gaps, and almost completely impossible for the larger module whose geometry prevented the filling of the hollow volume in its near entirety. Both pieces were then placed back inside the boxes and placed in the growth chamber for fourteen days. Starting with the inoculated substrate used as filling, a fairly rapid spread of mycelium from the inside out was observed. In particular, it was possible to observe as early as the second day the appearance of the first white areas that began to appear on the surface. The growth of the organism continued throughout the entire growth time only in the first of the two modules, however, slowing down significantly as the days went on and the surface of the printed artifact gradually lost moisture. In the second module, on the other hand, there was almost no growth of the organism which, after surfacing on the surface of the inoculated substrate, was unable to spread outward. In any case, for both pieces it can be said that mycelium growth on the clay occurred only superficially and inconsistently, leading to the growth of only a few hyphae and without creating a fungal skin. At the end of the fourteen days, the pieces were taken out of the boxes and it was immediately apparent that the moisture levels

Img.170
Parametric growth clay and hemp sample 1 after growth cycle and deactivation process.

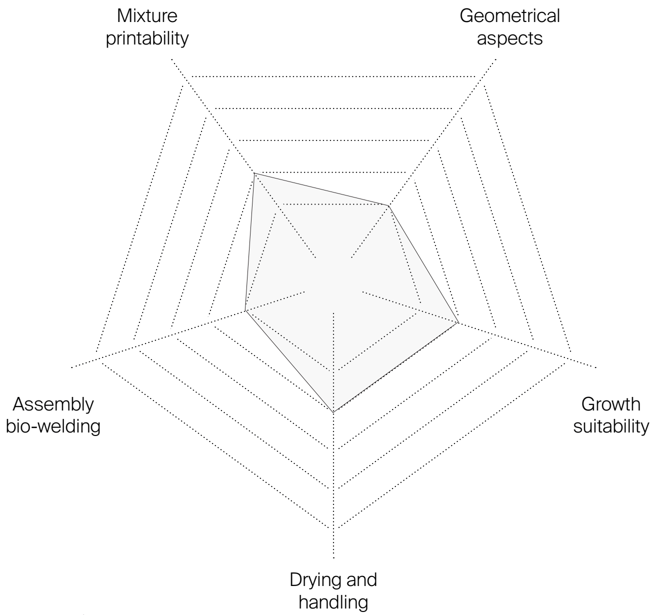
of the geometry were not at all compatible with proper development of the organism. The first module, however, exhibited obvious degradation of the basic geometry which, due to prolonged contact with water accumulated as condensation at the bottom of the box, partially dissolved, undermining the stability of the module and physically disrupting the connecting surface between the same piece and the second module. Parallel to this, the specimen in question showed no small amount of substrate colonization, leading to the creation of an MBC in the cavity filled by the material. However, the creation of the matrix affected the adhesion of the composite to the walls of the artifact leading during the same growth phase to a detachment of this increased following the deactivation phase of the organism. The first of the two pieces was then subjected to a two-hour temperature cycle at 120°C, at the end of which the fungal matrix became extremely yellowed due to exposure to the high temperature. It is therefore assumed that both the temperature and the duration of the cycle were excessive and led to degradation of the material. The second artifact in contrast was placed under normal atmospheric conditions and did not exhibit any particular changes in appearance since organism proliferation had been almost entirely absent to begin with. In summary, this experiment highlighted significant concerns regarding process sterility and the challenges in achieving uniform colonization of artifacts using an uninoculated mixture. Moreover, the approach of clay matrix colonization exposed issues related to shrinkage, likely influenced by the connection between the MBC and the UBWCC phases, particularly due to the introduction of the filling when the piece had considerably dried. Similar considerations apply to the clay-only sample in terms of geometry, where the presence of a continuous and intricate wall ensured stability during the printing phase but posed complications in the subsequent drying and filling stages.

Img.171, 172
Parametric growth clay and hemp sample 2 after growth cycle and deactivation under atmospheric conditions. Inaccurate stacking of the modules due to the partial bottom degradation of sample 1 caused by prolonged contact with water.



Img.173, 174, 175
3d priting process of Parametric growth clay and hemp samples 1-2. The intricacy and the corrugation of the geometries were paramatrically designed to enhance stability during printing and to favor the organism's growth through the creation of humidity niches and the proximity of walls to be filled by the fungal matrix.

Img.176
Parametric growth clay and sawdust sample 1.



Img.177
Radar chart of the sample's attributes.

MIXTURE COMPOSITION
Clay 50%, Kineco.bio sawdust inoculated with Ganoderma Lucidum 23,5% (0.5-3mm particle size), water 25%, flour 1,5%

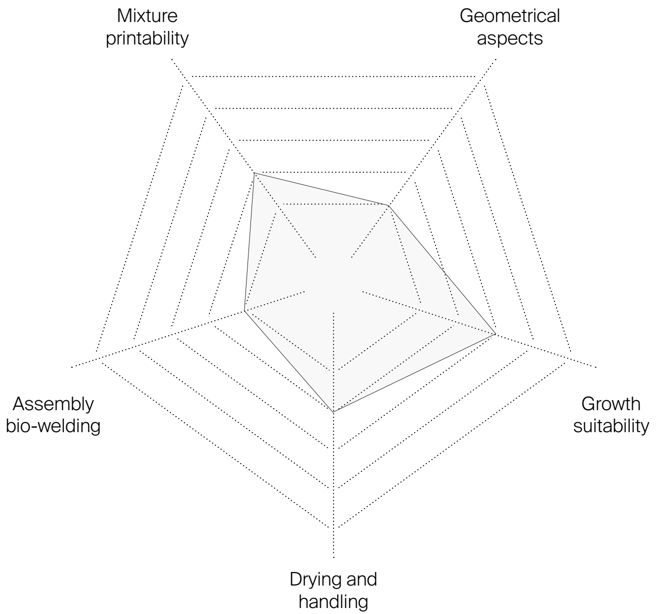
GEOMETRY TRAITS AND MAIN QUALITIES
Single wall, continuous intricate paths, computational modelling, modularity

FILE PROCESSING DATA AND WORKING PARAMETERS
Nozzle: 5mm
Layer Height: 1.5mm
Pressure: 4-4.5 bar
Printing time: 10mins

HYPOTESIS AND SUM OF OBJECTIVES
Layer definition evaluation, mixture inoculation before deposition, growth behaviour of the organism during process phases, comparision of different growing conditions

GROWTH CONDITIONS
Growth period: 8 days growth placed in growth chamber, no wrapping
Average environmental temperature and humidity: 26°C, 80%
Deactivation: dried at 120°C for 1hr and 30mins

Img.178
Parametric growth clay and sawdust sample 2.



Img.179
Radar chart of the sample's attributes.

MIXTURE COMPOSITION
Clay 50%, Kineco.bio sawdust inoculated with Ganoderma Lucidum 23,5 % (0.5-3mm particle size), water 25%, flour 1,5%

GEOMETRY TRAITS AND MAIN QUALITIES
Single wall, continuous intricate paths, computational modelling, modularity

FILE PROCESSING DATA AND WORKING PARAMETERS
Nozzle: 5mm
Layer Height: 1.5mm
Pressure: 4-4.5 bar
Printing time: 35mins

HYPOTESIS AND SUM OF OBJECTIVES
Layer definition evaluation, mixture inoculation before deposition, growth behaviour of the organism during process phases, comparision of different growing conditions

GROWTH CONDITIONS
Growth period: 8 days growth placed in growth chamber, no wrapping
Average environmental temperature and humidity: 26°C, 80%
Deactivation: dried at 120°C for 1hr and 30mins

^ Img.180
Details of parametric growth clay and sawdust sample 1 showing no growth of organisms on the piece's bottom surface and yellow stains on the upper layers due to contamination occurred during drying. Difficult removal of the piece from the MDF base due to excessive drying.

^ Img.181
Close-up view of the cracking occurred on the parametric growth clay and sawdust sample 2 after deactivation and due to excessive residual moisture and thermal shock.

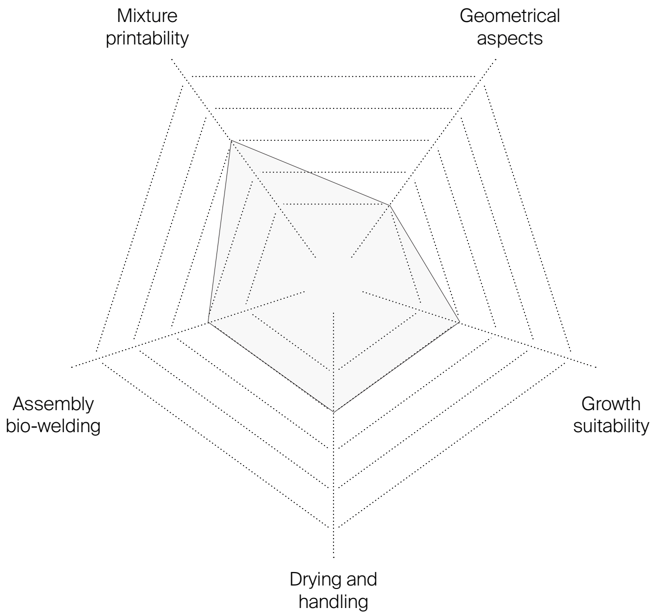
OBJECTIVES, RESULTS AND REFLECTIONS

The examined samples are part of a series of experiments involving the use of an inoculated mixture before the material deposition. Specifically, these artifacts were created during the very first printing trial for the author of a mixture containing the inoculated substrate. Their purpose was to evaluate the organism's response to the entire process, rather than focusing on how the geometries facilitate growth and assembly. Therefore, the study investigated the mycelium's ability to proliferate due to its handling during mixture preparation, stress from passing through machine components, prolonged exposure to a non-sterile printing environment, and its behavior within the growth chamber.

The 3D model used for the experiment was identical for both samples, resembling one of the modules in the preceding test and maintaining the same Gcode while preserving the layer height ratio. Consequently, the use of a customized 5mm diameter nozzle led to excessive material flow and suboptimal material deposition, causing an uncontrollable increase in wall thickness. Printing was terminated prematurely in both cases due to the inadequate print definition, preventing a comprehensive analysis of the geometries. The extrusion pressure needed for the blend was similar on average to that observed with the inoculated hemp-based blend, although it should be noted that the latter was extruded from a nozzle nearly half the size of the one used in this study. The quality of the layers, compromised by an incorrect ratio of their height to the nozzle size, was visibly less defined compared to the extrusion of the clay-only and clay mixtures supplemented with hemp powder. Notably, the flow exhibited more irregularities and graininess due to the disparity in size between the clay and sawdust particles, with a tendency to tear around the layer's curves.

With the aim of testing the growing influence variables within the growing box, the two artifacts were placed inside it in different ways. Specifically, one of the two was simply placed in the space resting on its print base, while the second was covered with a layer of plastic film wrapped around the print base. As early as the second day of growth, the appearance of fine hairiness and a lightening of the color of the material could be seen on the surface of the geometries, which became clearly visible from the third day. However, starting from this very moment, differences in growth between the two pieces to be compared began to be observed. The sample wrapped in film, and then exposed to an environment now saturated with carbon dioxide, continued to show a steady proliferation of mycelium until the creation of a more or less consistent fungal skin that concurred with a loss of visibility of layer definition. In contrast, the second sample directly exposed to the inner environment of the growth chamber exhibited a slowing of the growth rate until it gradually stopped, resulting in greater visibility of the printing layers than the comparative sample. Furthermore, in parallel with less consistent growth, the sample not wrapped in plastic film appeared drier and characterized on the top of the geometry by the appearance of yellowing of the material attributable to contamination. After eight days, both artifacts were extracted from the growth chamber and removed from the printing bases, whose porosity of the material (MDF) made it difficult to detach. Despite this, no organism growth was found on the support surface of either artifact, suggesting this phenomenon wasn't influenced by differing drying or contamination factors. Subsequently, both samples underwent deactivation at 120°C for an hour and a half. The sample that had shown more consistent growth remained intact post-baking but developed cracks and fractures shortly after, likely due to its moisture content during the firing process and the thermal shock when brought back to room temperature without there being a gradual transition. This hypothesis is also supported by the appearance of blue molds on the already deactivated piece, a sign that the surface had moisture conditions suitable for the development of contaminants.

Img.182
Clay and sawdust wall blending sample 1.



Img.183
Radar chart of the sample's attributes.

MIXTURE COMPOSITION
Clay 50%, Kineco.bio sawdust inoculated with Ganoderma Lucidum 22,5% (0.5-3mm particle size), water 25%, flour 1,5%, 1% xanthan gum

GEOMETRY TRAITS AND MAIN QUALITIES
Modularity, double wall perimeter, blending of walls through intersection, fast-to-print geometries

FILE PROCESSING DATA AND WORKING PARAMETERS
Nozzle: 5mm
Layer Height: 2.5mm
Pressure: 3,5-4 bar
Printing time: 10mins

HYPOTESIS AND SUM OF OBJECTIVES
Effective contact surfaces, enhancing base detachment through the creation of a bottom, bio-welding

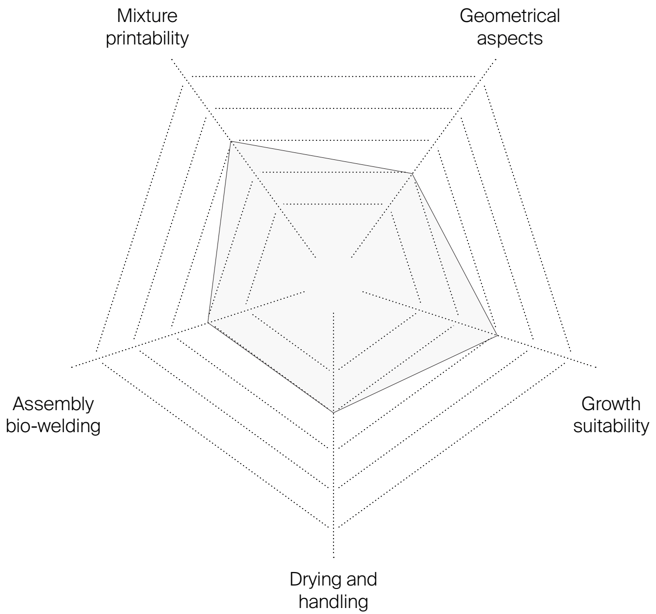
GROWTH CONDITIONS
Growth period: 8 days individual growth + 4 days in-contact surfaces growth wrapped in plastic film
Average environmental temperature and humidity: 26°C, 80%
Deactivation: dried at 120°C for 2 hours

Img.184
Bio-welding of two specimens connected through vertical walls. Design of hollow volumes to promote artifact's lightness while assembling.

OBJECTIVES, RESULTS AND REFLECTIONS
The examined specimen is part of a series of experiments conducted to investigate the potential for enhancing stability through the intersection and fusion of artifact walls. This approach involves modeling single-wall geometries with closely spaced folds, initially interpreted as independent walls by slicing software but merging during material deposition due to the larger layer size compared to the nozzle. In pursuit of this objective, the created geometries were intentionally simplified, emphasizing well-defined contact surfaces to assess functionality during bio-welding. Specifically, the analyzed sample features a volume conisisting on a double-walled C-shaped cylinder designed to facilitate welding at the curvature contact points during layer deposition. To enhance the contact surface area between modules and enable the stacking of more than two pieces, a bottom was incorporated. This served the dual purpose of facilitating removal from the print base without compromising the integrity of the thin vertical walls. However, the geometry exhibited an inherent tendency to shrink inward during printing due to the absence of wall corrugations, thereby compromising its stability.

A new element introduced involved incorporating xanthan gum into the printing mixture to assess its impact on increasing compound viscosity and facilitating continuous deposition by minimizing the likelihood of tearing. The use of this thickening agent proved advantageous for achieving the specified objectives, without causing significant alterations in working parameters compared to previous experiments. This time, file processing included an optimal ratio of nozzle size to layer height, which was increased to 2.5 mm. Despite the implementation of xanthan and adjustments to the mentioned parameters, the observed issue of low layer definition was attributed not so much to material flow through the machine, which exhibited a relatively smooth extrusion, but rather to the granularity of the mixture, resulting in considerable surface roughness. Mixture was identified as excessively dry, hindering proper adhesion of the walls to be welded, particularly in geometries with minimal contact points between walls. The cylindrical modules were left on the MDF base and incubated inside the growth chamber for eight days. No discernible changes were noted in the organism's growth process with the addition of xanthan to the printing material. Consistent with results from other tests, the side facing the printing base showed no signs of mycelium proliferation due to restricted air access. Additionally, owing to the inherent nature of the base material, the specimen's bottom was notably dry during separation, heightening the risk of complications due to solidification and partial attachment to the MDF. Following the initial individual growth phase, two modules were interconnected via vertical walls and left to grow for an additional four days. Subsequently, they underwent a thermal cycle at 120°C for two hours. Despite previous observations of deactivation modes in other samples, this approach was kept based on fractures observed in the preceding specimen. The modules were ultimately found to be securely connected, although the structure's complete cavity rendered the piece highly fragile.

^ Img.185
Clay and sawdust wall blending sample 2-3.



^ Img.186
Radar chart of the sample’s attributes.

MIXTURE COMPOSITION
Clay 50%, Kineco.bio sawdust inoculated with Ganoderma Lucidum 22,5% (0.5-3mm particle size), water 25%, flour 1,5%, 1% xanthan gum

GEOMETRY TRAITS AND MAIN QUALITIES
Modularity, blending of walls through intersection, compatibility of connection surfaces, fast-to-print geometries

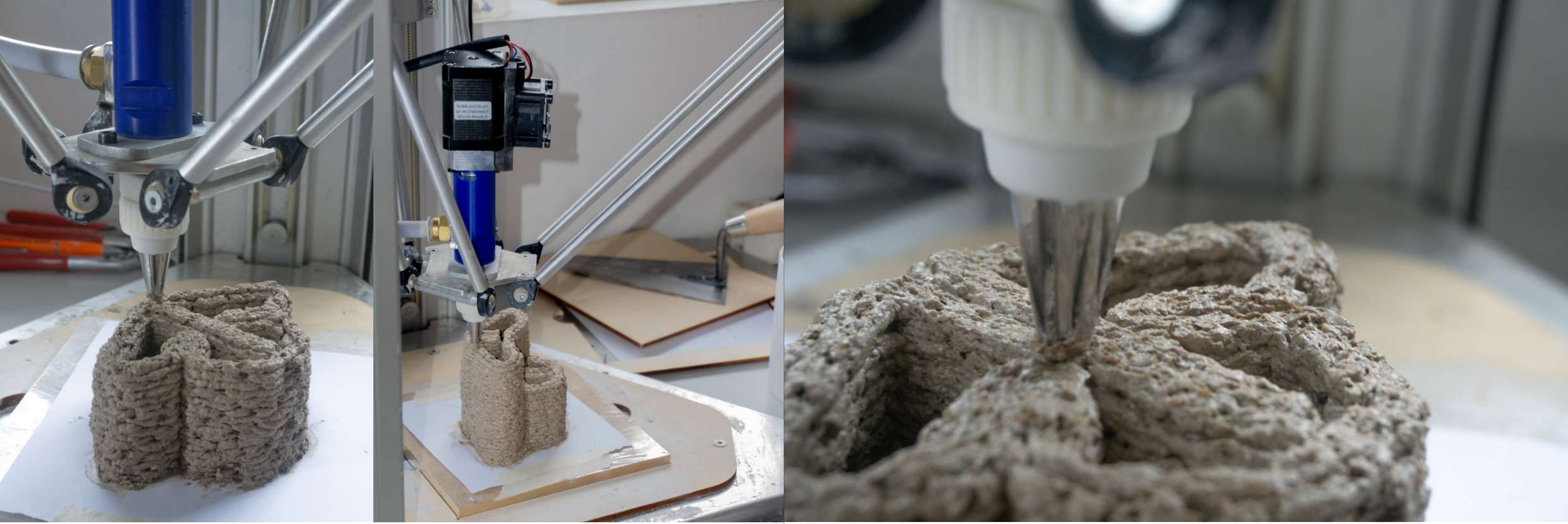
FILE PROCESSING DATA AND WORKING PARAMETERS
Nozzle: 5mm
Layer Height: 2.5mm
Pressure: 3,5-4 bar
Printing time: 20mins

HYPOTESIS AND SUM OF OBJECTIVES
Effectiveness of contact surfaces distributed across multiple directions, evaluation on the paper sheet in-betwenn print base and the artifact, increase of colonisable surfaces, bio-welding

GROWTH CONDITIONS
Growth period: 8 days individual growth + 4 days in-contact surfaces growth wrapped in plastic film
Average environmental temperature and humidity: 26°C, 80%
Deactivation: dried at 120°C for 2 hours

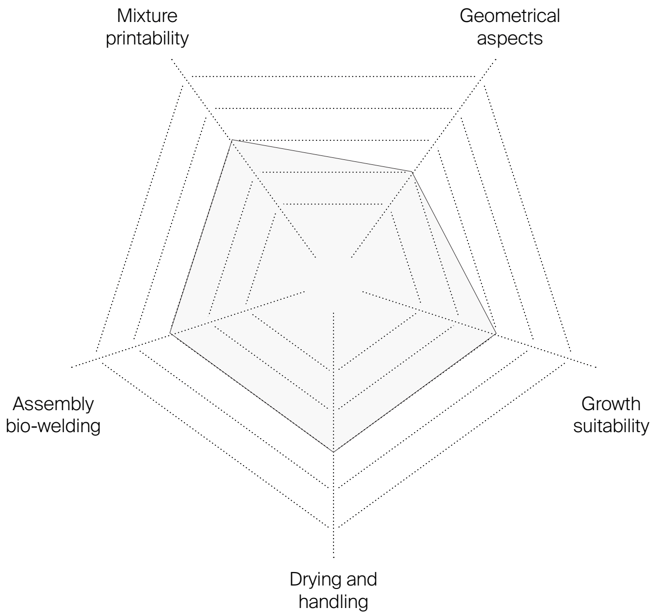
^ Img.187
Bio-welded specimens connected through the use of geometrical features to increase contact area distributed across multiple directions.

OBJECTIVES, RESULTS AND REFLECTIONS
Similar to the previous example, the two samples featured in these pages revolve around experimentation geared towards achieving stable geometries through the intersection of walls. Concurrently, the exploration of connection features between diverse modules took center stage in this experiment. Design considerations were particularly oriented towards enhancing the contact surface area, distributed across multiple directions. Photographic evidence reveals that both artifacts exhibit geometries specifically crafted to interlock when assembled and stacked. Both items follow a uniform section up to half of their 10cm total height, after which they diverge in a staggered manner. The decision to connect smaller modules through specific interlocks and prioritize stability through wall fusion, as opposed to intricate geometries, stems from the aim to reduce printing times compared to the parametrically modeled first geometries on Grasshopper. This strategy serves a dual purpose: firstly, to minimize the exposure window to external organism contamination, and secondly, to mitigate the likelihood of printing errors arising from air bubbles, extruder or nozzle clogging, particularly concerning irregular particle sizes. The printing mixture remains consistent with the previous sample, introducing xanthan as an ingredient for the first time. Consequently, considerations related to material extrudability and weak bonding between walls due to a low water percentage remain applicable. During the printing process, a layer of paper served a dual purpose by being placed between the printing base and the geometry. Its objectives were to facilitate separation between the artifact and the MDF and to offer the mycelium an additional organic substrate to encourage growth, even on the surface not exposed to air. While the first hypothesis proved successful, the second yielded results inconsequential to mycelium proliferation. Simultaneously, it hindered the observation of the organism’s behavior due to the paper’s white color adhering to the background surface. Despite the geometric designs aiming for inter-wall bonding, the low hydration of the mixture resulted in poor adhesion between contact points, preventing the intended outcome. The deposition process revealed a distortion of the vertical walls in both modules, intended as points of contact during connection, adversely impacting the adhesion between them. Both pieces underwent individual growth for eight days inside the grow box, followed by assembly and an additional four days of in-contact growth. Upon completing the growth cycle, they were deactivated by baking at 120°C for two hours. Despite the initial poor adhesion, it became evident that the modules had permanently welded together, showcasing the mycelium’s excellent binding capacity during the four days of contact. The use of geometries with cavities contributed to lightening the piece and increasing the surface area available for organism colonization, resulting in heightened compactness and improved handling during assembly stages.



Img.188, 189, 190
3D printing process of the specimens through the use of the custom nozzle, which enabled blockage-free extrusion of the mixture containing a substrate larger than 1.5mm. The large size difference between the clay sediment and sawdust particles resulted in a loss of layer definition and a tendency for the material to tear during deposition. The implementation of xanthan gum was a key component in achieving better extrudability of the mixture and a partial increase in print definition.

^ Img.191
Clay and sawdust wall blending sample 4.



^ Img.192
Radar chart of the sample's attributes.

MIXTURE COMPOSITION
Clay 50%, Kineco.bio sawdust inoculated with Ganoderma Lucidum 22,5% (0.5-3mm particle size), water 25%, flour 1,5%, 1% xanthan gum

GEOMETRY TRAITS AND MAIN QUALITIES
Modularity, blending of walls through intersection, compatibility of connection surfaces, fast-to-print geometries

FILE PROCESSING DATA AND WORKING PARAMETERS
Nozzle: 5mm
Layer Height: 2.5mm
Pressure: 3,5-4 bar
Printing time: 7mins

HYPOTESIS AND SUM OF OBJECTIVES
Use of orientated vertical walls as connection surfaces between pieces, increase of colonisable surfaces, bio-welding, plasitc printing base to promote detaching

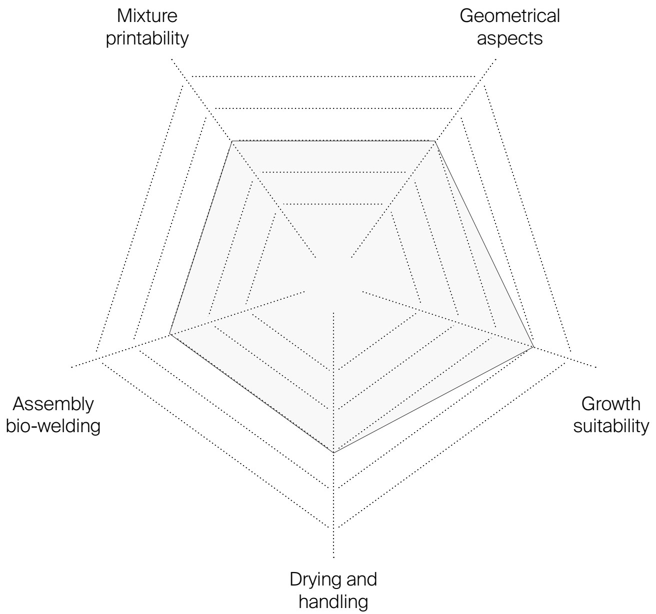
GROWTH CONDITIONS
Growth period: 8 days individual growth + 4 days in-contact surfaces growth wrapped in plastic film
Average environmental temperature and humidity: 26°C, 80%
Deactivation: dried at 120°C for 2 hours

^ Img.193
Clay and sawdust wall blending sample 4, bio-welding between modules.

OBJECTIVES, RESULTS AND REFLECTIONS
The experiment's sample was crafted with the same objectives as previous investigations, focusing on enhancing artifact stability through the design of interconnected wall geometries. The goals also encompassed maximizing colonizable surfaces and investigating the bio-welding properties of the organism. Consequently, the modules feature substantial vertical walls with a consistent 0° and 45° angle, serving as lateral guides for connecting with other components. Because of their compact size, approximately 5cm in height, these modules showcased rapid printing with minimal failure rates. This is attributed to both the shortened printing times, reducing the window for potential issues, and the presence of stable geometries supported by corrugations and a strictly vertical development. The printing mixture employed here aligns with that used in samples from previous experiments on inter-wall welding, as all were printed from the same material in a single tank fill. As a result, observations regarding the mixture's suitability for inter-wall welding geometries remain applicable in this context.

The shapes, arranged on a plastic base, underwent an eight-day growth period. Subsequently, they were brought into contact with each other and returned to the growth chamber for an additional four days to facilitate bio-welding. The material of the printing base facilitated artifact removal without adhesion, eliminating the need for forceful separation. Due to the base's impermeability, the surface in contact with it retained moisture, remaining damp when the modules were flipped, creating favorable conditions for mycelium colonization. In fact, a principle of organism growth restart was observed even on these surfaces that had not been observed so far with all other samples placed in contact with porous printing bases. To deactivate the modules, a temperature cycle of 120°C for two hours was employed, solidifying the bond between them. The fungal matrix exhibited satisfactory quality, enabling the pieces to connect during the period of contact growth. However, degradation occurred at points where the material was touched during assembly or detachment from the base, a material behaviuor observed in all the specimens fabricated so far via 3D printing. Across all samples exploring inter-wall welding, which involved ribbed geometries, superior organism growth within the cavities was noted compared to the quality found on the external surfaces. This resulted in the formation of a softer, thicker skin that exhibited better preservation even after completion of deactivation cycles.

Img.194
Clay and sawdust bricks sample 1.



Img.195
Radar chart of the sample's attributes.

MIXTURE COMPOSITION
Clay 45%, Kineco.bio sawdust inoculated with Ganoderma Lucidum 22,5% (0.5-3mm particle size), water 30%, flour 1,5%, 2% xanthan gum

GEOMETRY TRAITS AND MAIN QUALITIES
Modularity, infill design, surface's features of connection, vertical walls, fast-to-print geometries

FILE PROCESSING DATA AND WORKING PARAMETERS
Nozzle: 5mm
Layer Height: 2.5mm
Pressure: 2,5-3 bar
Printing time: 12 mins

HYPOTESIS AND SUM OF OBJECTIVES
Different module's orientation for printing and for assembling, increase of colonisable surfaces, evaluation of the geometrical effectiveness of the contact surfaces, vertical arrangement of welding layers, bio-welding

GROWTH CONDITIONS
Growth period: 6 days individual growth + 4 days in-contact surfaces growth placed in plastic boxes
Average environmental temperature and humidity: 26°C, 80%
Deactivation: dried at 100°C for 1hr and 30mins

Img.196
Detail of the bio-welding process between modules through the designing of connection features to increase contact surfaces on multiple directions. This solution resulted inconsistent due to the difficulties encountered to obtain precise geometry with the material mixture.

OBJECTIVES, RESULTS AND REFLECTIONS
This experiment introduces several innovations when compared to prior studies, implementing insights into the organism's behavior during 3D printing and the existing growth constraints. The primary focus of the test was to explore assembly methods aiming to optimize the mycelium's bio-welding capabilities by increasing effective contact surfaces and concurrently mitigating technical and aesthetic issues arising from the uneven growth of the fungal skin on the printed parts' undersides. To address these challenges, a novel assembly strategy was devised, involving a different orientation of the modules relative to the printing direction. Specifically, this approach relies on additive fabrication of geometries with at least two perfectly vertical walls. By rotating these structures 90° during assembly, two extensive colonized surfaces align parallel to the ground at the connection point between pieces on each level. Additionally, the assembly method involves inward placement of the previously uncolonized face toward the ground, ensuring a visually cohesive development of the organism on every visible surface. Following this logic, an extra 90° offset in the XY plane for consecutive level modules facilitates connection through an alternating brick wall-like arrangement. This arrangement maximizes contact between modules, creating flat surfaces parallel to the ground and enhancing the overall structural integrity of the assembled pieces. The other objective pursued within the experiment involved the design of an infill geometry defined on the basis of two main variables: the ability to ensure stability of the artifact both during printing and assembly by bearing the vertical weight through the infill walls, and also to encourage emptying of the internal volumes with the aim of reducing the weight of the pieces and promoting fungal skin growth over as large an area as possible. The development of a consistent layer of fungal material was a critical point in this experiment since on the one hand it aimed to contribute to the mechanical behavior of the modules during assembly, preventing their deformation due to the weight of the different stacked pieces, and on the other hand the proliferation of the organism was essential for the assembly logics just described.

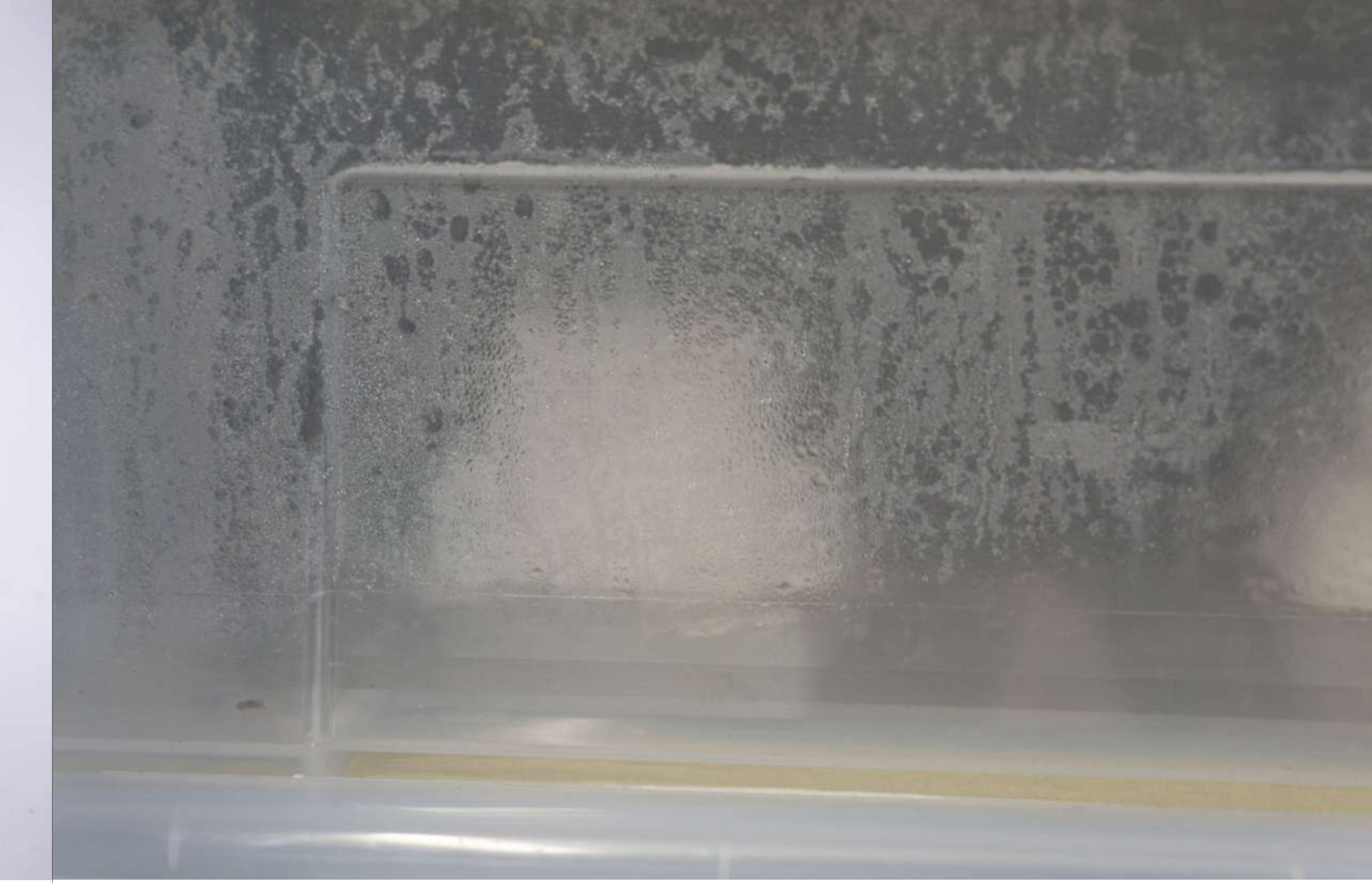
To this end, therefore, two infill geometries generated within the slicing software were explored, namely fast honeycomb and full honeycomb. The infill types, both characterized by the presence of a stable hexagonal pattern, differ from each other in the presence or absence of a constant double wall between the various cells of the geometry. Given the small size of the modules and the high infill rates set at the file processing stage, the result in both cases was a dense mesh within the perimeter geometry. The experiment also possessed an additional level of investigation related to how surface design affected the behavior of the organism during assembly. For this reason, for the purpose of assembly, two geometries were made, each of which had a feature prepared for interlocking with the following piece. At the same time, however, one of the two pieces in addition to the contact feature on one of the two sides also possessed a completely flat wall, designed to connect to the

Img.197
Detail of the bio-welding process between modules through the designing of flat surfaces to increase the contact area. This solution was found to be most useful for ensuring correct adhesion between the pieces by exploiting the weight of the material that kept the surfaces in contact during the growth process of the binding matrix.

following piece via this and thus compare the effectiveness of different types of contact surfaces for the purposes of the bio-welding process.

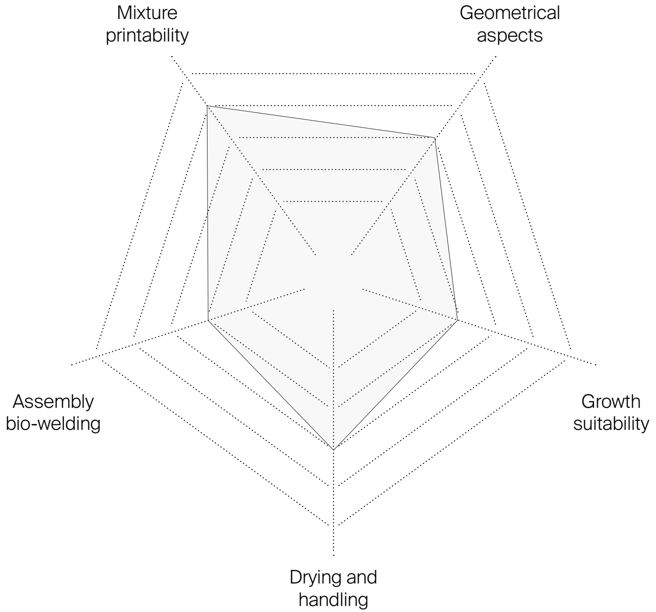
The mixture composition utilized during the printing phase underwent adjustments based on observations made thus far. Specifically, the water content was increased to enhance adesion between walls during deposition, a crucial element for fabricating geometries with internal infill. Concurrently, an upsurge in xanthan gum was introduced to balance the added water, preserving the mix's viscosity and elasticity. However, the revised mixture proved overly liquid. Given the small size of the infill cavities, this led to excessive expansion of the deposited flux, resulting in diminished print quality and, notably, infill volume. Despite the persistence of infill cavities, the enlarged inner walls reduced the available air contact surfaces for developing a fungal skin. Subsequent to molding, the forms were subjected to a six-day growth cycle inside plastic boxes, exhibiting a remarkably high-quality fungal skin. The accelerated and consistent growth surpassed previous samples. The pieces' elevated humidity positively contributed to organism proliferation. Assessing the thickness of the fungal layer achieved, the individual growth period was deemed adequate. Following the described assembly logic, the pieces were interconnected for an additional four days. Due to the high water content and the presence of a thick outer fungal layer hindering drying, the assembled structure distorted. The excessive softness of the pieces and the lower modules struggling to bear the weight of numerous upper ones contributed to this distortion. Nonetheless, the strategy of implementing internal infill geometries succeeded, with partial deformation observed primarily at the bottom, while the remaining modules effectively supported the weight above.

After the four-day period, the structure was removed from the box and subjected to a temperature cycle of 100°C for 1.5 hours. Considering insights from prior experiments, particularly the fungal matrix quality achieved after heat treatment at 120°C for two hours, a decision was made to reduce the time and temperature parameters to preserve the quality and, notably, the brilliance of the blank. Following deactivation, the pieces were found to be permanently and securely assembled, displaying excellent overall adhesion that permitted post-baking manipulation of the structure without module separation. The assembly logic was thus stated successful, enabling the creation of a firmly interconnected structure with all external surfaces uniformly colonized by mycelium. Regarding the connection points between modules, it was noted that flat surfaces proved more effective in ensuring adherence between pieces compared to the interlocking feature, which encountered issues in matching the involved surfaces.



Img.198
Detail of the formation of moisture on the container walls produced by the organism's metabolism during the growth process.

^ Img.199
Clay and hemp bricks sample 1.



^ Img.200
Radar chart of the sample's attributes.

MIXTURE COMPOSITION
Clay 50%, Smush's hemp powder inoculated with Ganoderma Lucidum 22,5 %(0.1-0.5mm particle size), water 25%, flour 1,5%, 1% xanthan gum

GEOMETRY TRAITS AND MAIN QUALITIES
Modularity, infill design, surface's features of connection, vertical walls, fast-to-print geometries

FILE PROCESSING DATA AND WORKING PARAMETERS
Nozzle: 5mm
Layer Height: 2.5mm
Pressure: 3,5 bar
Printing time: 12 mins

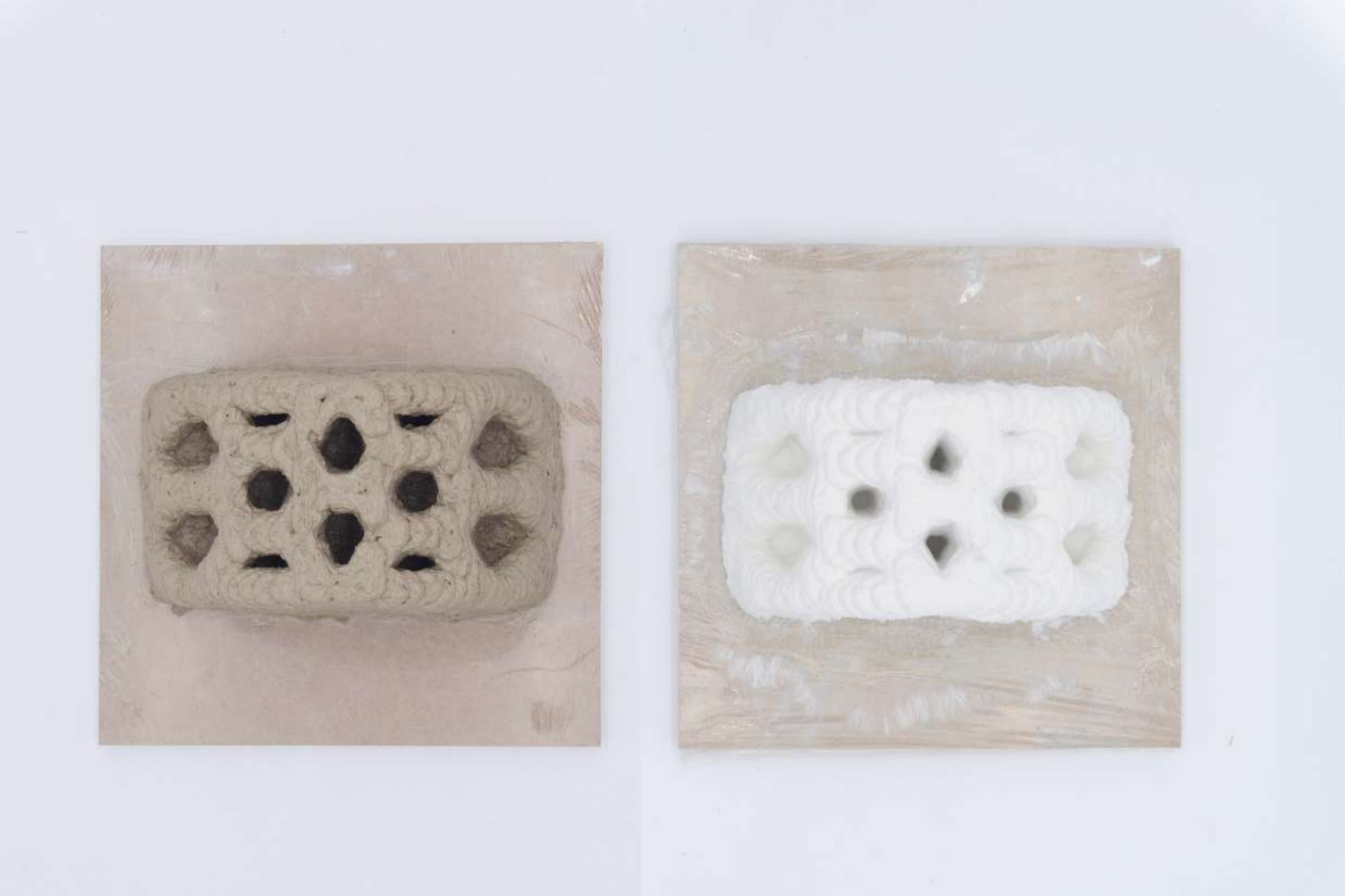
HYPOTESIS AND SUM OF OBJECTIVES
Different module's orientation for printing and for assembling, increase of colonisable surfaces, evaluation of the geometrical effectiveness of the contact surfaces, influence of a pre-growth phase of the mixture prior to deposition

GROWTH CONDITIONS
Growth period: Mixture pre-growth period 14 days before printing process,6 days individual growth placed in plastic boxes
Average environmental temperature and humidity: 26°C, 80%
Deactivation: dried at 100°C for 1hr and 30mins

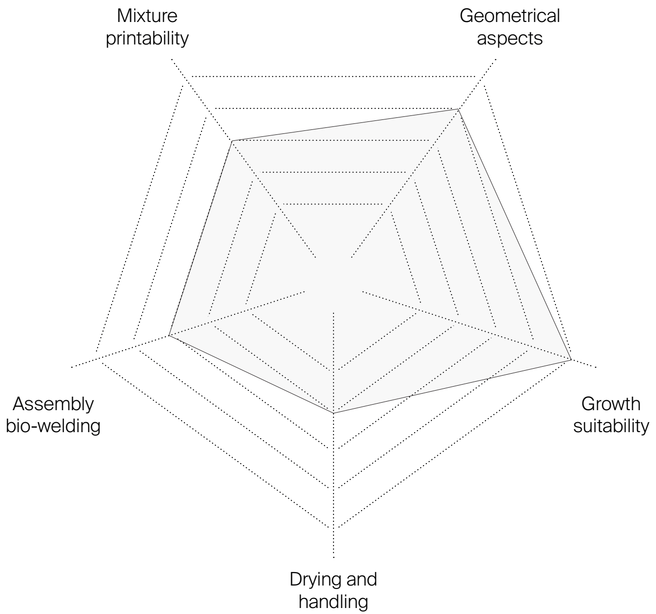
^ Img.201, 202
Assembly logic of modules in regard to their printing direction and influence of different filling pattern in generating hollow volumes to allow an increase of colonizable surface area by the organism.

OBJECTIVES, RESULTS AND REFLECTIONS
Similar to the preceding experiment, the samples in this analysis were generated to assess the efficacy of an assembly method based on a distinct orientation for printing and connecting pieces. The goal was to test the creation of infill geometries ensuring artifact stability during mixture deposition and module assembly while exploring the impact of contact surfaces on optimizing the organism's bio-welding properties. Hence, considerations related to the modeling and processing of geometries remained consistent with the previous sample.

The divergence from the prior experiment lies in the use of a different mixture for constructing the modules. In this instance, a fourteen-day interval occurred between the preparation of the printing paste and its deposition in the 3D printing process, allowing the mycelium to proliferate during this period. Photographic documentation reveals the surfacing of white areas on the mixture exposed to air, not in contact with the plastic envelope. The hypothesis aimed to assess whether a pre-growth phase directly in contact with the clay matrix before deposition could positively influence the organism's behavior. To this end, the mixture was thoughtfully crafted based on the proportions specified by the Smush materials startup, involving inoculation of hemp powder with Ganoderma lucidum. This new substrate coincided with a reduced water content in the mixture, a choice influenced by the unsatisfactory definition of infill geometries observed in previous attempts. The printing of the modules showcased enhanced layer definition, attributed to the minute size of the dispersed phase and the optimal water content in the mixture, preventing excessive flux compression during deposition. Subsequently, the pieces underwent individual growth for approximately six days, yet their development was halted due to the organism's sluggish and inconsistent progress. Heat treatment at 100°C for one and a half hours deactivated the pieces. It can be deduced that the pre-growth phase of the mixture before deposition did not effectively support the organism's growth. Instead, it subjected the organism to prolonged exposure to conditions unsuitable for proliferation, adversely affecting its final growth behavior.



Img.203
Clay and sawdust semicylinders sample 1 before and after mycelium colonisation.



Img.204
Radar chart of the sample's attributes.

MIXTURE COMPOSITION
Clay 45%, Kineco.bio sawdust inoculated with Ganoderma Lucidum 23% (0.5-3mm particle size), water 28,5%, flour 2%, 1,5% xanthan gum

GEOMETRY TRAITS AND MAIN QUALITIES
Modularity, infill design, increase of hollow volumes, flat vertical walls of connection, rounded volumes

FILE PROCESSING DATA AND WORKING PARAMETERS
Nozzle: 5mm
Layer Height: 2.5mm
Pressure: 2-3 bar
Printing time: 25-50 mins

HYPOTESIS AND SUM OF OBJECTIVES
Module's orientation for printing and for assembling, increase of colonisable surfaces, bio-welding of discrete dimension artifacts, artifact's texturing based on geometry and spatial arrangement, assemby inserts, post-deactivation contamination

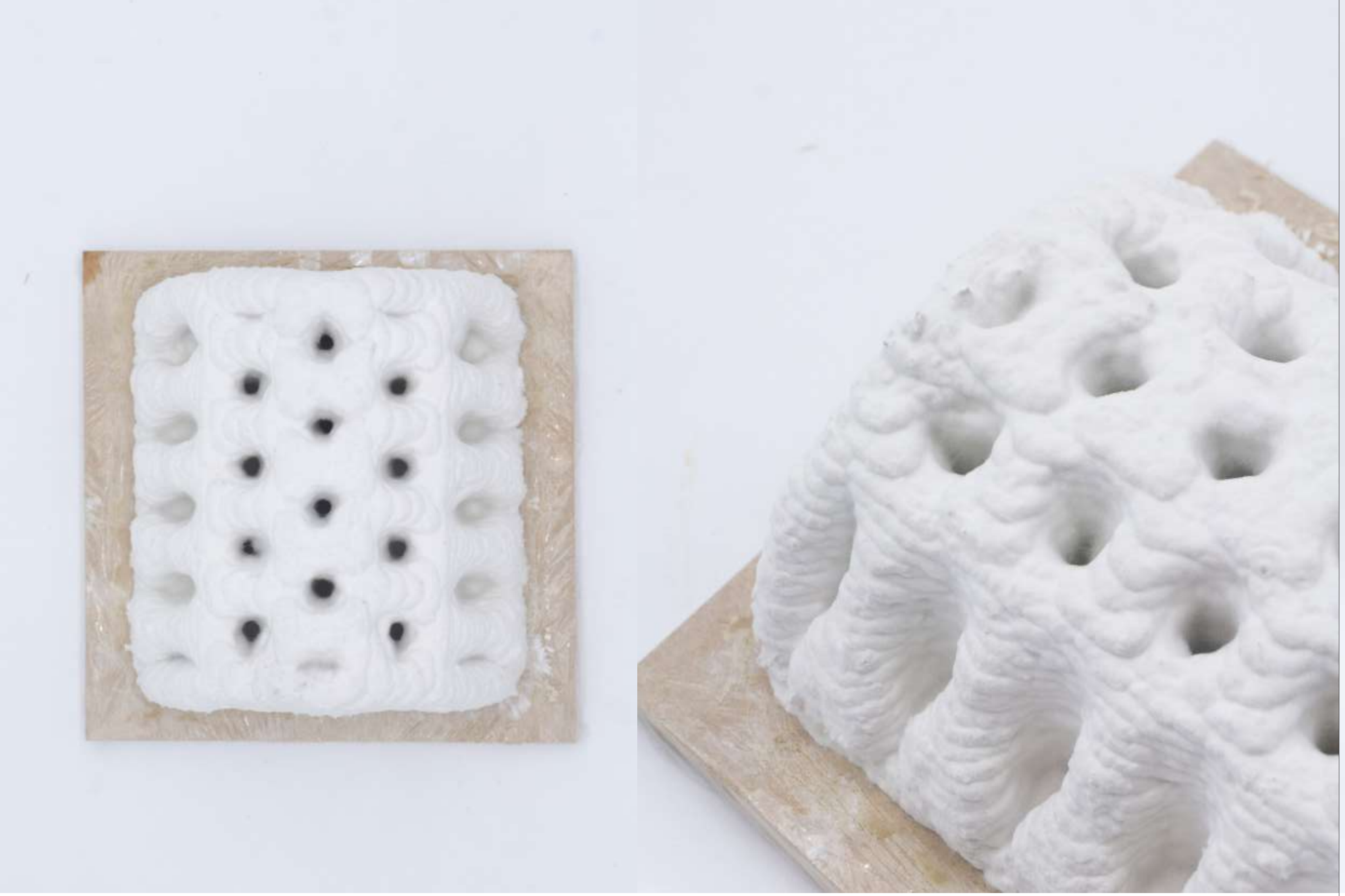
GROWTH CONDITIONS
Growth period: 8 days individual growth + 10 days in-contact surfaces growth placed in plastic boxes
Average environmental temperature and humidity: 23°C, 80%
Deactivation: dried at 85°C for 45mins and at 120°C for 2hrs

Img.205
Front and side views of the clay and sawdust semicylinders sample 1.

OBJECTIVES, RESULTS AND REFLECTIONS
The experiment aimed to explore previously uncharted aspects, closely aligning its objectives with those outlined in the final stages of chapter five and subsequently detailed in the project's outcome. The focus of the investigation was primarily on defining geometries, revealing that the implementation of infill walls serves a dual purpose: ensuring stability during the printing phase and fostering organism growth by creating voids that enhance aeration and expand the colonizable surface area. Recognizing the necessity of incorporating this geometric element into the design for both sealing and mycelium compatibility, we delved into the exploration of how this distinctive aesthetic quality could contribute to defining the overall texture of greater artifacts when assembling multiple modules.

To achieve this objective, a double-walled hexagonal infill geometry was created, designed to be sufficiently large for clear visibility of cavities while preventing potential hindrance to material deposition due to nozzle size and printing pressure. This time the infill geometry was 3D-modeled rather than generated during the file processing stage, allowing for a semicircular shape while maintaining control over the print path and internal geometries. This approach ensured the consistent presence of a double wall, a feature challenging to achieve using preset options in slicing software. Multiple modules were produced with a consistent modeling logic for the semicircular shapes, varying in size by a factor of two. The exploration of these volumes primarily aimed at aesthetic considerations. The previous successful assembly method involved constructing levels in halves oriented differently from the printing direction and progressively staggering them, offering a strategy free from formal constraints. Surface connections parallel to the ground allowed freedom of rotation in the XY plane, enabling the generation of a revolving geometric texturendefined by infill cavities. All modules incorporated three bottom layers to enhance stability and prevent deformation during manipulation and detachment from the print base. The mixture composition was adjusted by using less clay and more water to achieve well-adhered geometries. Despite the initial shift towards larger artifacts, requiring a substantial amount of printing time due to more complex geometries and a regular, relatively narrow infill pattern, the printed parts exhibited excellent stability. However, the considerable weight of the modules, ranging from 600g to 1000g for two types of half-cylinders, posed a challenge due to their size and increased water content in the mixture. Some of the shapes were printed on MDF bases covered with plastic film and some directly on print bases made of plastic material, with no observed differences in organism growth among individual samples based on this variable.

All molded pieces, intended to form a structure approximately 40cm in height once interconnected, were positioned inside boxes and the growth chamber, where they underwent individual growth for about 8 days. Despite variations in growth conditions due to the colder season



Img.206, 207
Clay and sawdust semicylinders sample 2. Top view and detail of the geometries.

Img.208, 209
Combined structure of clay and sawdust semicylinders 1-2, bio-welded. Detail of the threaded metal inserts into the clay matrix.

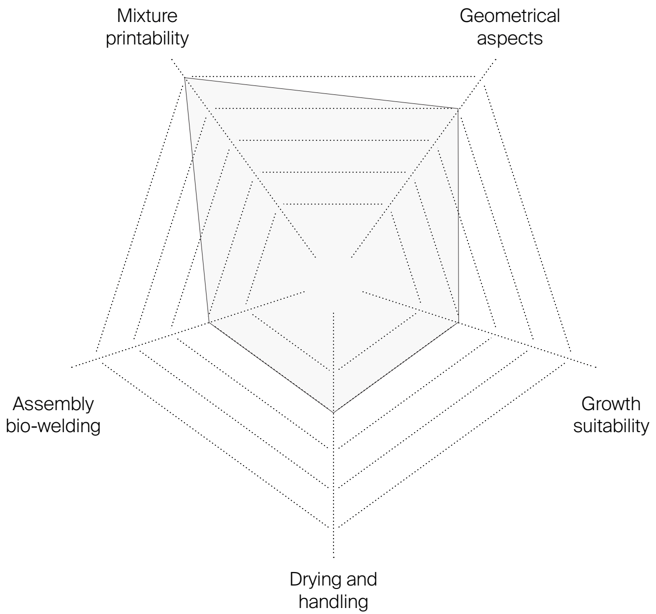
and the heating mat's inability to surpass 23°C, the modules exhibited satisfactory fungal skin formation. During connection, pieces with superior growth, correlating with increased overall stiffness, were intentionally chosen for the base. For the base modules, holes were drilled on the bottom surface, and metal inserts were added to serve as junction points for future feature insertion. The assembly occurred over two separate days, creating two half-structures that were joined after an additional four days. While assembling the two halves, each composed of four pieces, a slight deformation in geometries was immediately noticed due to structural instability and the weight of the pieces, particularly at contact points between levels and at the base. Additionally, consistent material shrinkage on the Z-axis during the drying of the pieces resulted in an inaccurate assembled volume and the formation of an oval rather than a circular section when modules were rotated and connected. Following an initial collective growth period to allow further drying, the two half-structures were finally brought together, leading to further deformation. The total weight of the structure was 5kg, indicating a loss of about 500g from the initial measurement during printing due to piece drying. Although the deformation did not cause a collapse, the assembled structure irreparably folded, resulting in numerous cracks and tears, especially near the volume cavities.

After the subsequent growth phase, the structure underwent deactivation in an oven, subjected to a gradual thermal cycle reaching 85°C in 45 minutes, followed by a stable temperature of 120°C for approximately two hours. Despite experiencing partial collapse, the specimen remained securely assembled due to the binding action performed by the organism. The substantial weight of the structure likely contributed positively to the mycelium's ability to form a strong bond, maintaining contact between layers throughout the growth period. Despite extensive thermal cycling, the overall structure retained significant moisture, attributed to its large size and the printing geometry with a relatively thick bottom. Following baking, the artifact was placed on a shelf in the Polifactory space under normal environmental conditions. After about a week, contamination of the structure became evident, marked by the formation and growth of blue-green patches on its surfaces. This contamination resulted from a combination of high residual moisture in the material and handling following thermal treatment, allowing other organisms to infect the piece without competition from the deactivated mycelium. Most visible contamination concentrated in areas of higher moisture, such as cracks and geometrical cavities, spreading onto the non-living fungal matrix. The artifact was subsequently moved outside for space hygiene reasons and to observe the material's behavior during prolonged exposure to weathering events. Over the following weeks, the structure experienced prolonged contact with water due to rainy weather, simulating an environment where the material is dispersed and naturally degrades over time. Despite the lack of a scientific method in this improvised experiment, observations revealed the fungal layer's resistance to water contact, behaving as to a natural plaster on the clay matrix. Following water exposure, additional organism growth occurred, including the appearance of mosses near the object's cavities. As of writing this section, the artifact exposed outside for fourteen days displayed no significant signs of degradation, aside from a loss of white gloss, progressive yellowing, and the emergence of brown mottling in some areas on the surface.

Img.210, 211
Detail of contamination on the combined structure of clay and sawdust semicylinders 1-2. Growth of several kind of organism was observed on the surfaces due to unsufficient drying and handling of the pieces which led to the outbreak of green-blue mold and black dots.

Img.212, 213, 214, 215
On the left page detail of the printing process with the deposition of an excessive liquid mixture which affected layer definition and accuracy of the geometries, close-up view of the boxes with custom lids inside the tent during the growth cycle of the organism. On the right page details of assembly logic performed within the test which highlited structural issues due to the artifact weight but proved successeful the method of orientating the modules to ensure bio-welding between them.

Img.216, 217
Clay and sawdust semicylinders sample 3.



Img.218
Radar chart of the sample's attributes.

MIXTURE COMPOSITION
Clay 51%, Kineco.bio sawdust inoculated with Ganoderma Lucidum 25% (0.5-3mm particle size), water 21,5%, flour 2%, 1,5% xanthan gum

GEOMETRY TRAITS AND MAIN QUALITIES
Modularity, infill design, increase of hollow volumes, flat vertical walls of connection, rounded volumes, scaled geometry to anticipate shrinking behaviour

FILE PROCESSING DATA AND WORKING PARAMETERS
Nozzle: 5mm
Layer Height: 2.5mm
Pressure: 3,5-4 bar
Printing time: 16 mins

HYPOTESIS AND SUM OF OBJECTIVES
Module's orientation for printing and for assembling, increase of colonisable surfaces, bio-welding of discrete dimension artifacts, artifact's texturing based on geometry and spatial arrangement, assemby inserts, post-deactivation contamination

GROWTH CONDITIONS
Growth period: 6 days individual growth placed in plastic boxes
Average environmental temperature and humidity: 23°C, 80%
Deactivation: dried at 85°C for 45mins and at 120°C for 2hrs

Img.219
Detail of the organism's hypae spreading on the clay matrix.

OBJECTIVES, RESULTS AND REFLECTIONS
This experiment aimed to address the deformation issues encountered during the assembly phase of the previous test. It involved designing a support structure for the modules to ensure an even distribution of loads. Specifically, the resizing of geometries to simultaneously reduce weights was complemented by implementing a vertical stacking system comprising a support base and a perpendicular threaded bar. On the vertical structure, the two modules and a PLA disk, positioned on a nut, were systematically arranged on each level, repeating the sequence six times. The disk featured a ribbed geometry and hollow volumes arranged radially, resembling the appearance of a lemon slice, with the goal of facilitating vertical communication between the various levels of the object. The functioning of the stacking system was conceptualized based on the principle that, as the discs abutted against the nuts, and the nuts were prevented from descending due to the threading, the load of the weights would be distributed along the bar rather than on the individual pieces. As a result, the colonized pieces were expected to fuse across the designated space, solidifying the bond and submerging the discs within.

The modules were printed using a new mixture composition that showed the best level of layer definition observed so far among experiments using sawdust as a dispersed phase. Due to a mixture prepared several days earlier than the actual printing phase, growth of the organism was extremely slow and problematic and was interrupted while nevertheless continuing the experiment even in the absence of the fungal matrix. During connection of the modules, a noncylindrical section was again observed, due to shrinkage of the part and dimensional reduction in the Z axis. Once the structure was assembled, it was left to dry at atmospheric conditions for a few days. Within this time window, there was detachment of the levels due to the role played by the nuts in preventing the disk from accompanying the shrinkage of the parts. In addition, the discs were found to be too thick and too large in size, leaking out of the structure and thus becoming extremely visible. As the layers became detached, a loss of the structure's axis and subsequent bending due to the weight exerted by the material and not discharged directly to the ground was then observed. The experiment, considered overall a failure both from the point of view of the growth of the organism and from the point of view of the functioning of the assembly system, nevertheless laid the basic foundation for the assembly methodology of the final output that we will observe in the next chapter.

ANALYSIS OF RESULTS

6.3

Having completed the on-field investigation phase, we can now provide an overview of the results obtained from implementing cultures, samples, processes, different spaces and equipment during the four exploratory sections. Specifically, given the overlapping of the various areas of experimentation and the influence that each had in conditioning the choices made and approaches used during the following phases, downstream process considerations can be traced back to the five segments related to 3D printing practice where the variables involved are most observable overall. Through the rounds of experiments, it was possible to gain insight into the behavior of the hybrid material and the cultivation and fabrication processes necessary to define a full understanding of the organism. Some of the goals stated prior to the material exploration phase in the field were achieved and demonstrated during the realization of tests and samples, specifically the creation of a colonizable mixture inoculated prior to the deposition phase, obtaining a consistent development of the organism, and improving the properties of the hybrid material compared to raw clay and UBWCCs while maintaining its complete biodegradability. To fulfill the ultimate goal of producing discrete-sized objects through LDM printing, leveraging the organism's bio-welding property, and proposing a design methodology for process repeatability, it is essential to summarize the attained results. This summary, along with the underlying rationale, will guide the definition of the final project output and the realization of the demonstration prototype in the concluding phase of this research thesis.

6.3.1

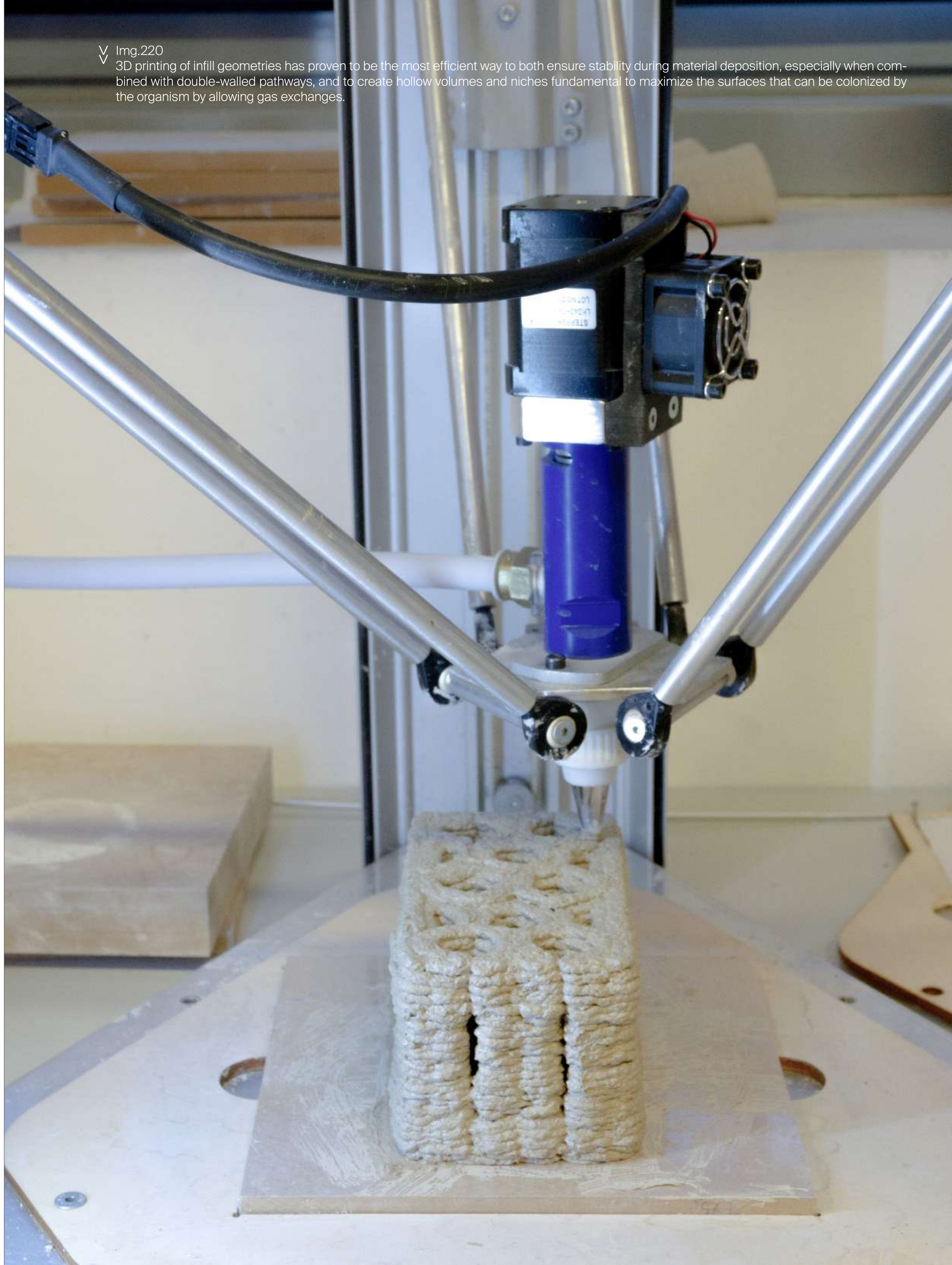
Printing mixture

Throughout the conducted tests, an in-deep examination of numerous variables concerning the composition of the printing mixture for digital fabrication of artifacts was undertaken. Specifically, the experiments aimed to establish a recipe for the printing material, involving different stages of the process that impacted not only the deposition stage but also the preceding substrate cultivation stage. In relation to this, diverse approaches to cultivating the organism were tested to obtain a substrate of minimal size, potentially free from spawn, to enhance the extrudability of the compound. Despite less-than-ideal results in individual experiments regarding the initiation of fungal cultures, it was observed that the Hedel composite substrate exhibited significantly better growth performance than the self-produced material. This also signified that the chosen method for inoculating the artifact did not involve filling but was solely associated with the combination of ingredients within the printing mixture itself. Recognizing the inherent challenges in replicating the material performance of a commercially available engineered organism, and considering the research's focus on objectives beyond cultivating the fungal strain from scratch, the decision was made to use pre-inoculated sawdust from third-party sources as the substrate in the final prototyping phase. With the substrate determined and sizing issues addressed through the creation of a custom nozzle via an equipment hacking approach, attention turned to the remaining recipe ingredients and their proper proportioning in the mixture considerations.

The outcomes derived from the execution of the samples indicate that the incorporation of additives into the mixture had a notably positive impact on both the material deposition phase and the subsequent growth phase of the organism. Consequently, it is imperative to consider the addition of extra nutrients and thickening agents to the printing mixture. An optimal recipe, proportioned by weight, is recommended as follows: clay 50%, inoculated sawdust 21.5%, water 25%, flour 2%, xanthan gum 1.5%. Regarding the determination of the water quantity in the mixture, careful considerations are necessary. The amount of water influences the extrudability of the mixture, weld adherence between geometry walls, handling of the pieces, and the weight of modules during assembly. Therefore, the specified water percentage in the recipe is ideally calculated for the specific designed process of constructing the final prototype, directly tied to growth-drying times and assembly logic. While this value is universally suitable for achieving easy extrusion with the equipment used, it's crucial to tailor it to the particularities of the process. Addressing the issue of lower print definition due to the dispersed phase nature was resolved by incorporating xanthan, considered acceptable concerning the formation of the fungal skin, which contributed to its enhancement. The resulting mixture successfully attains the first objective of the thesis—producing an extrudable compound allowing organism colonization and pre-deposition inoculation into the clay matrix.

6.3.2
Geometry constraints

Relative to the considerations regarding the strategies for defining the geometries to be adopted, it is possible to define some requirements that these must comply with in order to ensure the structural tightness of the artifact at the printing stage, but also to positively affect the later stages of the process related to the proliferation of the organism, the handling of the pieces and their assembly. The experiments particularly reveal the need for mainly hollow geometries so as to maximize the surfaces that can be colonized by the mycelium, which can possibly be obtained by fusing the walls of the artifact so as to ensure greater stability and avoid its collapse during printing and assembly. The fabrication of smaller modules was found to be a better performing strategy for the purposes of the printing process itself and for that of drying, removal from the bases and handling. Relative to aspects of the material deposition process, the generation of small artifacts was found to be instrumental in reducing printing time and potentially verifiable process error components due to issues related to flow interruption, bubble formation during tank filling and contamination. Printing small forms has simultaneously contributed to limiting the vertical development of artifacts and circumventing structural stability issues of geometries that could cause parts to collapse. The ideal geometries defined according to the assembly logic adopted contemplated the development of at least two flat vertical surfaces to be exploited when connecting parts to simplify and maximize at the same time the contact points between different modules. In general, an approach was adopted that characterized the artifacts from different fabrication and assembly directions, vertical and horizontal, respectively. Finally, the addition of some bottom layers to the artifact contributed to the contribution of stability during printing and to facilitate the removal and handling of the parts in the later stages by preventing the intricate geometries of the infill from being deformed during these actions.



Img.220
3D printing of infill geometries has proven to be the most efficient way to both ensure stability during material deposition, especially when combined with double-walled pathways, and to create hollow volumes and niches fundamental to maximize the surfaces that can be colonized by the organism by allowing gas exchanges.

6.3.3

Growth cycle variables

The practices and experiments conducted in all four sections of the on-field material investigation had a direct influence on the understanding of the organism's growth variables, on the estabilishment of the ideal conditions in which to operate for the purposes of its proliferation, and on the qualitative aspects of its development on which to intervene projectually through the collaborative practice established between designer, organism and digital fabrication media. By setting up a dedicated growth space, it was possible to have control over the parameters and conditions under which the manufactured samples were cultured, a prerogative that is indispensable for the purposes of advancing the research and achieving the goals of colonizing the clay matrix. The primary influencing factors considered were temperature, humidity, ventilation of clean air, carbon dioxide accumulation, absence of light and cleanliness of the spaces and instrumentation involved. Other variables, however, influenced the results at different stages of the process even if not directly related to the prepared growing space. These include the composition of the mixture relative to the use of additives and the correct amount of water, the design of the geometries and the timing of the growth cycle performed.

Relative to the setting of the growth space, the most influential variable was found to be the use of specially modified containers in which to have mycelium development take place. These containers consisted of simple boxes whose lids were suitably modified with micro holes or filter material that allowed gas exchanges even though maintaining high carbon dioxide saturation levels on the inside. This on the one hand facilitated the management of the CO2-O2 ratio of the space immediately surrounding the pieces, and on the other hand further controlled the drying behavior of the material while also influencing potential contamination factors to which one was always exposed by not being able to guarantee a completely sterile working environment. The combination of this equipment with the growth tent contributed to the effective proliferation of the organism that successfully colonized the clay matrix verifying an additional objective among those stated prior to the field investigation phase. Space temperature was the least influential variable and, accomplice to the months in which the fabrication of the samples took place, between spring and autumn, did not result in substantial differences in the quality of the fungal skin despite relatively wide ranges between 20-30°C. Internal humidity, on the other hand, was regulated through the use of a humidifier that consistently maintained levels above 80 percent. A side note to the process is that during the summer the humidifier needed to be refilled with water extremely frequently while during the colder months the relative humidity was kept averagely stable by both the produced water evaporated from the pieces, the metabolic processes of the organism and the fact that the growth tent represented an enclosed space capable of naturally retaining it inside.

Another crucial variable impacting mycelium proliferation, unrelated to the space itself, was the design of geometries featuring cavities and coves. This design proved essential in ensuring oxygen access for the organism and maximizing colonized surfaces. The entire fabrication and assembly of modules were oriented toward maximizing mycelium growth, guiding the process logics entirely toward this objective. Notably, mycelium growth was absent on the surface in contact with the printing plate, occurring only when pieces were detached and rotated 90°. Cultivation times varied, with the organism appearing on artifact surfaces from the second day, densifying the fungal matrix over subsequent days. While no defined minimum growth period was established, progress observations guided the decision on when to proceed to the next assembly stage. This decision balanced sufficiently advanced growth with proper drying to enable manipulation. Typically, after one week, the organism exhibited significant surface growth conducive to connecting pieces after another seven days of incubation.

Considering organism growth in relation to inoculation methodology, creating uninoculated artifacts and subsequently filling cavities with colonized substrate proved unsuccessful, as the lack of an autoclave compromised sterility. The preferable approach involved depositing a mixture where an inoculated substrate is already dispersed, initiating organism development uniformly over the entire surface during the wettest and most favorable time for wall adherence. Lastly, using a mixture previously inoculated and subjected to pre-deposition growth yielded unexpected results, hypothesized to have render the organism less performant due to prolonged substrate particle contact with air absence, immersed in the clay matrix.

6.3.4
Drying and handling

The drying process emerges as a critical factor for the overall success of the procedure, especially concerning the quality of experiments that involve assembling colonized modules. The humidity parameters in the growth space were determined not only to foster organism proliferation but also to facilitate slow and controlled drying, preventing artifact cracking due to rapid shrinkage. However, the excessively humid environment resulted in the clay matrix drying only until the piece's humidity balanced with the surroundings. In addition, drying was delayed due to the adherence of the surface in contact with the printing base, which did not allow proper release of excess water until the piece was tipped over. Relative to this then it became necessary, along with reasons related to growth on these surfaces as well, to manipulate the printed artifacts so as to promote an additional rate of drying. Using plastic material for printing bases or covering MDF bases with film facilitated this without compromising the forms. It was noted how, on the other hand, the deposition of the material directly on porous bases negatively affected this by on the one hand adhering the material to the surfaces and on the other hand over-drying it by preventing mycelium growth from occurring once the piece was separated from the base. In this sense, the design of stable geometries and the presence of a base made it easier to detach the geometries from the plane without substantial deformation of the piece occurring.

The creation of a thick fungal skin was also an important variable in the ease of manipulation of the colonized modules. It was observed that in the presence of consistent growth, the negative effect due to pressure exerted on the surfaces was reduced, which in the case of rough growth, on the other hand, resulted in a loss of the homogeneity of the surface matrix and led to the visibility of defects due to handling. To accommodate the assembly stage, where pieces needed to be touched and rotated, consistent fungal skin growth was essential. The thickness of the matrix layer formed by the organism actually resulted in elastic behavior of the piece which, even more than drying, was responsible for the ability of the modules to be manipulated and later stacked together without deforming under their own weight. Balancing drying time with the time needed for fungal matrix formation proved pivotal for the successful assembly of modules.

6.3.5
Assembly and bio-welding

The final aspect in analyzing the results of the process segments pertains to the assembly and bio-welding of the modules. The experimentation in these investigation areas involved creating a series of samples to explore the impact of the geometry of contact surfaces between modules, the required timing for the process, and the strength of the bonding matrix concerning discrete-sized artifacts. Upon investigating geometries and considering the integration of interlocking features between modules, it was determined that, due to challenges in obtaining precise prints, the most effective connection between parts occurs with flat and extended contact surfaces. The assembly phase, closely tied to geometric constraints, necessitated the development of a specific strategy based on a different orientation logic of the modules relative to the vertical printing direction. This connection method utilizes two perfectly vertical walls that, when the part is rotated 90° during assembly, align parallel to the ground. These walls serve as large, flat colonized areas, facilitating the connection between parts on each level. A subsequent 90° rotation, parallel to the ground plane, ensures a progressive vertical offset, enabling the connection of all parts through a brick wall-like arrangement where colonized flat surfaces maximize contact between modules. Moreover, employing this assembly principle with two mirrored halves per level allows the noncolonized surface facing the print base to be oriented internally. This results in artifacts where the single visible surface presents a homogeneous development of the organism.

This approach, followed by an additional growth cycle with the pieces in contact, demonstrated a strong bond between the pieces facilitated by the mycelium. However, due to deformations and collapse caused by weight, the assembly of discrete-sized objects emerged as the sole area of interest with unresolved critical issues at the conclusion of the material investigation. Another concern arising from the deactivation phase of large artifacts involves ensuring proper drying of the pieces through a temperature cycle that is simultaneously gentle enough to avoid damaging the fungal matrix and causing overly rapid drying. This is closely related to the vulnerability of incompletely dried artifacts to contamination phenomena. Once the competitive advantage of ongoing colonization by mycelium is removed, the artifact becomes susceptible to possible contamination by other organisms during the handling of the pieces. Regarding temperatures and the duration of the deactivation phase, these factors must be considered as variables depending on the actual size of the composite structure and the presence or absence of thick cavities or walls. In general, the temperatures explored and the duration of the process ranged from 90-120°C and 90-120 minutes, respectively. Deactivation by exposing the part to atmospheric conditions instead of temperature cycles resulted in an overall reduction in quality due to the degradation of the organism in an environment not conducive to its proliferation.

Specifically, issues related to assembly and deactivation represent the final unresolved obstacles to achieving the stated objectives of the thesis work and realizing the final project output constructed from the knowledge gained during the theoretical and field investigation phases. In the next chapter dedicated to defining the artifact type and creating the demonstration prototype, these challenges will be emphasized, and the strategies that facilitated their resolution will be presented.

CHAPTER 7

TERRAFORMA

7.1 FINAL OUTPUT DEFINITION

7.2 PROTOTYPING

... The current material investigation, culminating in the fabrication of a physical artifact, is therefore intended to propose concrete resolutive models of the contradictions exposed within it. Terraforma seeks to serve as a manifesto, highlighting the responsibilities and possibilities inherent in the design practices with which we choose to shape the environment we live in every day. Terraforma tells about a vision of progress that departs from the one traditionally associated to this word, it tells about a possible reality in which materials have the power to positively influence our choices and at the same time in which our species is called, once and for all, to orient the future toward sustainable practices ...

Img.221

FINAL OUTPUT DEFINITION 7.1

7.1.1

Codification of the final artifact

The research undertaken has followed a two-phase structure. Initially, a broad exploration delved into various issues, particularly focusing on the compatibility of UBWCCs and MBCs, leading to theoretical considerations. This was followed by a second phase dedicated to on-field verification of material experimentation objectives. Throughout the research, each aspect has played a role in shaping a comprehensive process where the designer's influence is central, guiding design dynamics through a co-design approach with the organism. In this context, fabrication technologies are employed as tools to facilitate collaboration, directing the growth of mycelium to achieve specific design goals. The formulation of these objectives in the current research arose from a cognitive void identified in the interaction between clay and fungal materials. The material investigation primarily addressed the need to validate hypotheses regarding the compatibility of these two material domains. Simultaneously, it aimed to define requirements for achievable qualities and process protocols, considering the opportunities and constraints arising from the dialogue between the organism and the digital fabrication technologies involved. To elaborate further, the preceding chapter summarized insights gained from field investigations regarding the organism's behavior in clay LDM printing processes.

In light of these and the stated objectives, it is now possible to define the project output through a process of codifying the final artifact that will be produced, understood as a systemic organization of processes and the formulation of qualitative specificities that will be incorporated into the project prototype. In particular, this practice follows the need to establish a clear set of guidelines and instructions for the design of geometries, their fabrication, cultivation and assembly. Indeed, the specificity and level of depth of the area explored requires that the choice of the final object type be linked to an assessment of constraints and opportunities that emerged from the results of the field analysis, in which design choices and approaches were entirely constructed based on the metabolic processes of the mycelium.

Field experimentation offered numerous answers regarding the initial hypotheses, demonstrating the possibility of combining clay and mycelium effectively and making a new hybrid material functional to

Img.222
Exhibition view from Damián Ortega's "CAPITAL Less" at Gladstone Gallery, 2009. In that body of work, Ortega created a series of concrete and brick blocks by pressure sanding them into irregular shapes. Equating the loss of material with both geological erosion and the waste of capital, Ortega conflates the action of creating sculpture with an economics of positive and negative spaces.

the stated objectives. It demonstrated, albeit in the absence of empirical measurements, a significant improvement in overall material qualities compared to greenware clay and UBWCCs. In particular, the result obtained downstream of the organism deactivation process and the complete drying of the pieces showed: an excellent mechanical strength of the composite guaranteed by the fiber bridging mechanism established between the clay matrix, dispersed phase and fungal coating matrix; a water repellent behavior and the loss of the water solubility of the material in medium-long time windows of exposure; and its complete biodegradability guaranteed by the absence of thermal processes aimed at the chemical modification of the material.

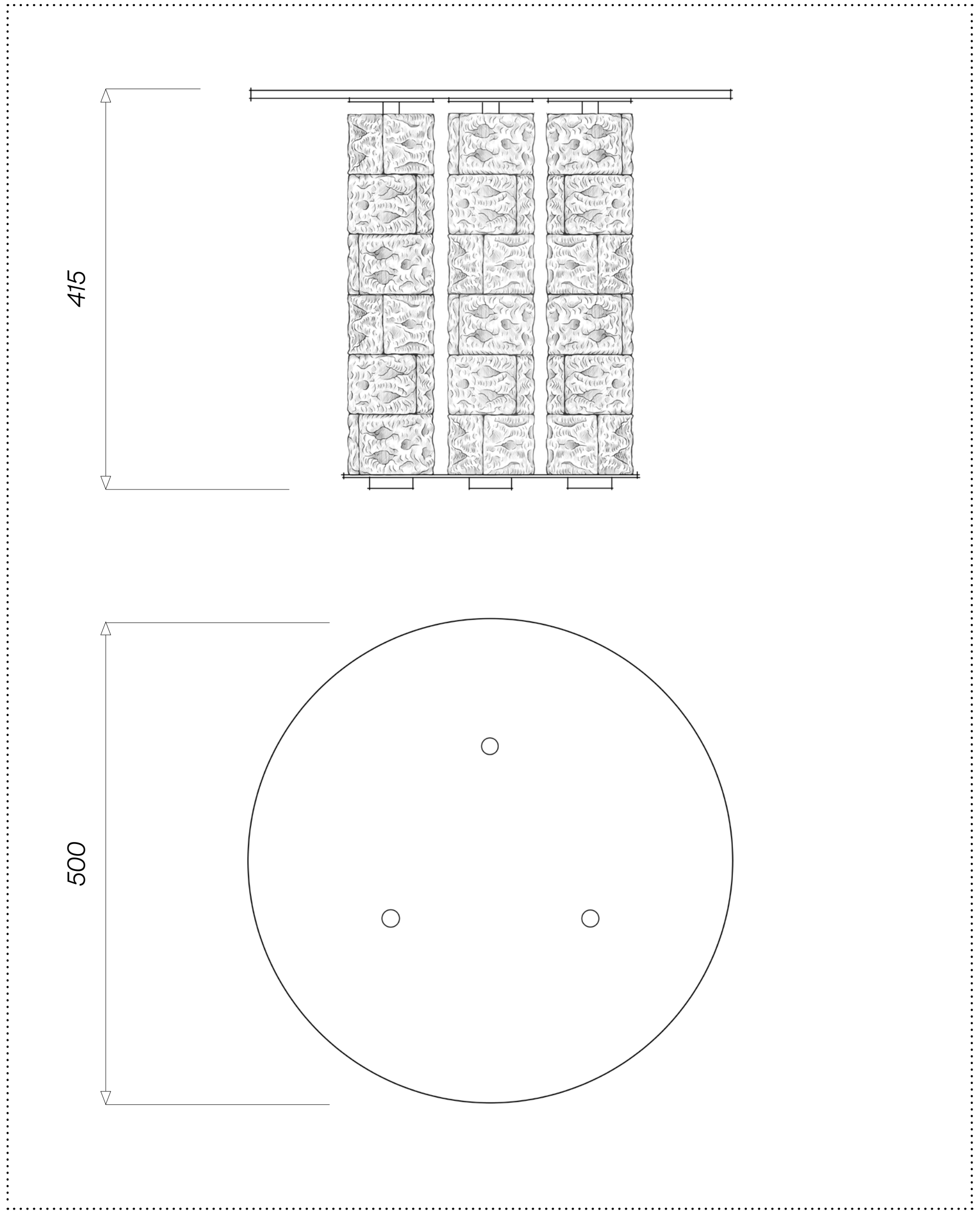
The creation of customized fabrication and assembly logics, fully defined to ensure the proliferation of the organism and the exploitation of its bio-welding methabolic properties, made it possible to verify the soundness of the goal of making an artifact of considerable size. Despite problems related to deformations due to shrinkage or collapse due the weight of the overall structure, which will later be addressed and definitively resolved in the final prototyping phase, the module connection methodology devised proved successful for the purpose of creating an effective binding matrix. The principle by which it operates is to contemplate different printing and assembly direction, allowing the various pieces to be connected rather freely if the requirement of having two flat surfaces as a point of contact is met. While the methodology has its limitations, such as a preference for vertical stacking over horizontal stacking, it remains effective. Vertical arrangement aids in maintaining adherence between contact surfaces, utilizing their own weight to form the binder matrix during the bio-welding process. This approach is particularly advantageous for artifacts developing along the vertical axis, allowing for dimensions beyond the traditional capabilities of the printer model used. The obstacles in this case are the weight problems of the modules and the size of the oven in which to perform the deactivation of the organism posterior to the joining phase of the pieces. In the case of the research in question, this translates into a dimensional constraint of 50cm in height given by the instrumentation available at Polifactory, namely an electric ceramic kiln with an internal loading volume of 50cmx50cmx50cm.

The assembly by staggering the modules along the vertical progression, in parallel with the geometric reasoning required for mycelium growth, allows for the creation of interesting textures when considering the degrees of freedom of arrangement of the modules in relation to the flat surfaces on which they are arranged. The possibility of rotating modules marked by the strong geometries therefore suggests that the object can be characterized by an aesthetic based on the texturization of the surfaces by the geometries themselves in combination with the living component of the fungal skin obtained from the growth of the organism. In the perspective of vertical development, it is therefore possible to experiment and play with these effects and to make up, thanks to the logics of assembly, for the loss of print definition due to the use of a mixture with non-homogeneous composition by giving an entirely different appearance to the colonized artifacts.

The suitability of the sequential set of processes of design, fabrication, cultivation and assembly to the realization of colonized modules to compose larger structures from vertical development, the possibility of giving them an aesthetic obtained by a mixture of geometric and growth factors, the dimensional constraints exposed, and the evaluation of the mechanical and physical properties of the hybrid material obtained, led to the determination that such an object demonstrating the application potential of this material is a coffee table. More precisely, such an artifact is proposed to be composed of a series of legs fabricated in the hybrid material in accordance with the processes and methods explored so far. This is dictated by the reflections that have been made regarding the constraints and opportunities that have emerged from the research and the definition of a design strategy consistent with the material qualities found. The object in question will therefore present a series of components made through the assembly of colonized modules and vertically connected to each other according to the logic illustrated through the metabolic processes of mycelium. The selection of the typology of the object and the definition of the role of the elements to which to assign the investigated material, finds its basis in the morphology and the role they play within the structural dynamics proper to the object itself. Specifically, given the mechanical performance offered by the hybrid material, it is assigned the role of bearing

FINAL ARTIFACT OVERALL DIMENSIONS

Img.223
Schematic representation of the final artefact to be manufactured as physical output at the end of the material investigation. General dimensions and overall view of the elements assembled to compose the coffee table. Scale 1:5.



stress loads proportionate to the type of artifact selected. Although this evaluation of material properties was not carried out through empirical measurements, the experimental results offer solid reasons for assigning the explored material to the supporting elements of the structure. This choice is not intended to be reductive, and the material applications could be alternatives, but the selection of the artifact is based on a compromise between the material characteristics, the logic of primarily vertical development of the achievable structures, the dimensional constraints of the output that can be produced with the available equipment, and the personal inclination for the design of furniture objects.

Hence, the final product will consist of three load-bearing elements crafted from the material under investigation. Specifically, each element will be constructed by assembling 12 modules interconnected through the organism's metabolism, forming a vertical progression across six levels, for a total of 36 pieces. In the production of the table legs, inserts and features will be incorporated to prepare these components for future assembly with other parts of the artifact. This will include a supportive base and levelling feet designed to adjust the coffee table's ground support. The upper section of the artifact will feature elements allowing for micro-adjustments in the column height, ensuring a support surface perfectly parallel to the ground. The necessity for these adjustments arises from the challenges in achieving perfectly identical legs, attributed to factors such as uneven material deposition during printing, vertical compression from module assembly, and parts shrinking during drying and deactivation.

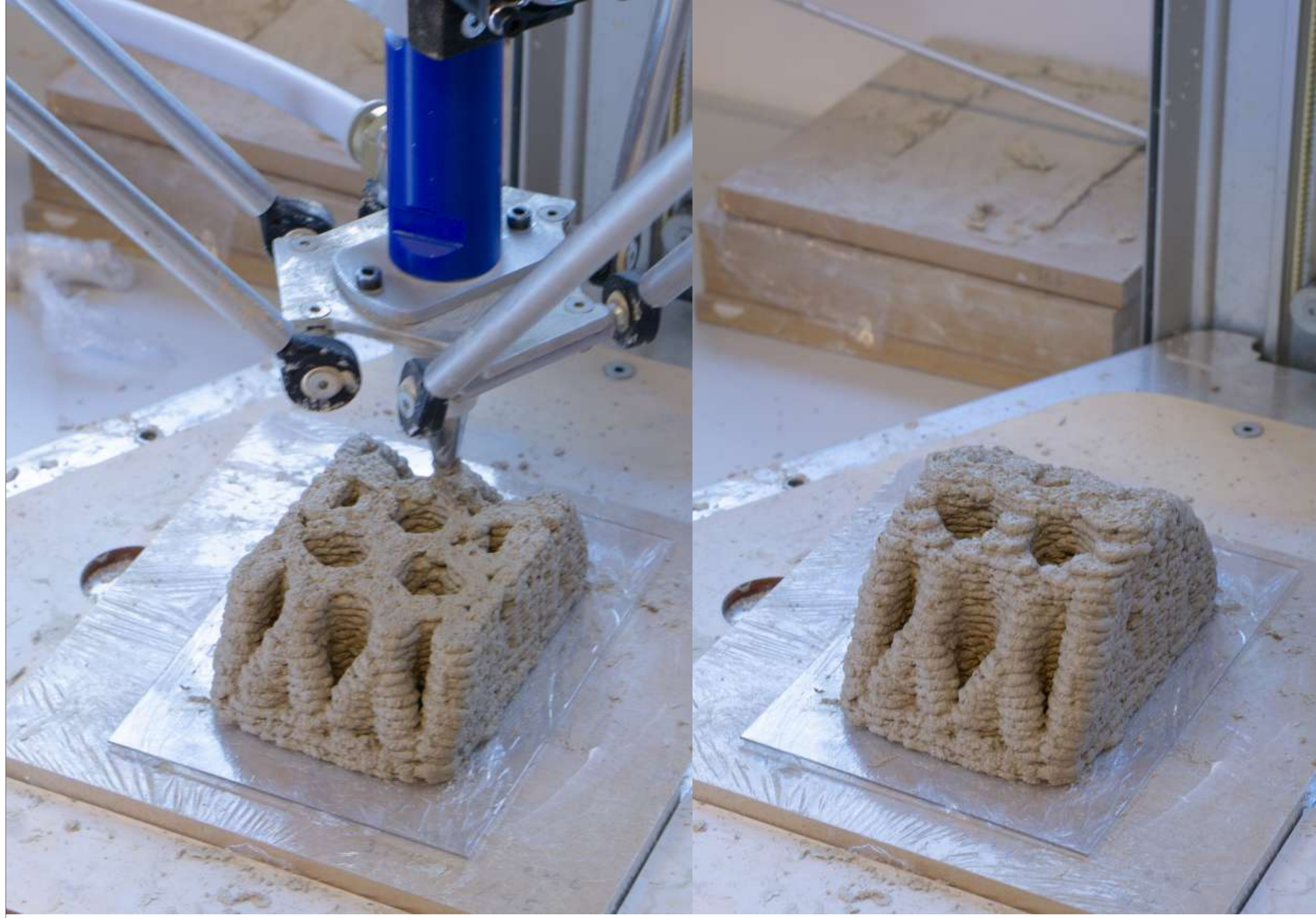
In the upcoming chapter, the prototyping process of the final artifact will be showcased, realized through cultivation, fabrication, and assembly processes identified as most promising during the material field investigation. The object will not only demonstrate potential material applications but will also embody a broader vision related to the potential of Digital Biofabrication processes.

TERRAFORMA PROTOTYPING
7.2

7.2.1
Printing process and growth cycle

After concluding the section on identifying the type of artifact to be manufactured and reflecting on the subsequent considerations, we will now delve into the process of fabricating the final prototype. Transforming the initial samples into a tangible product to meet specific objectives required careful planning of activities. This ensured that the fabrication, cultivation, and module connection steps occurred in a timely and cohesive manner. The breakdown of the process analysis into three distinct areas—molding and growing, assembly and deactivation, and prototyping of third-party components—originates from the implementation of additional strategies to address previously unresolved issues compared to past experiments.

The first area of analysis focuses on printing the pieces and on their initial growth cycle. These internal activities within this section were conducted based on the most promising results from testing, incorporating targeted interventions to enhance the quality of the obtained modules. Regarding the design of the geometries, it was decided that the coffee table's legs would independently follow a vertical development, as explained earlier in this chapter. The logic of modeling and fabricating the geometries from the latest samples in section 6.2.4 was adopted. This involved creating cylindrical structures assembled in levels, each composed of two halves. The overall modeling phase incorporated essential requirements identified during the field investigation phase such as: increasing colonizable surface area by designing hollow volumes, ensuring stability during printing with a double-walled infill pattern, minimizing the modular size to prevent printing failures and reduce contamination windows, adding a bottom for ease of detachment from the printing base, and incorporating flat vertical walls to align with the defined assembly logics. The efficacy of these aspects was previously demonstrated during the 3D printing phase of material experimentation. However, in this final prototyping stage, two additional strategies were employed to enhance output quality. The first strategy focused on adjusting the wall thickness assigned to the geometries during both 3D modeling and file processing. Even in the experimental phase, manual infill pattern modeling was deemed more effective than generating it during processing for greater control over the double-walled nature of the geometries. To ensure efficient welding at the intersection of single walls, the 3D file creation and g-code generation processes were based on a theoretical nozzle size smaller than the one used for the actual material deposition. Modeling single-wall geometries with a thickness of 4mm, combined with path generation based on this information, allowed the use of a 5mm nozzle to create a more effective intersection, resulting in more stable prints and parts with a more compact internal structure capable of better supporting the weight of other modules during assembly.

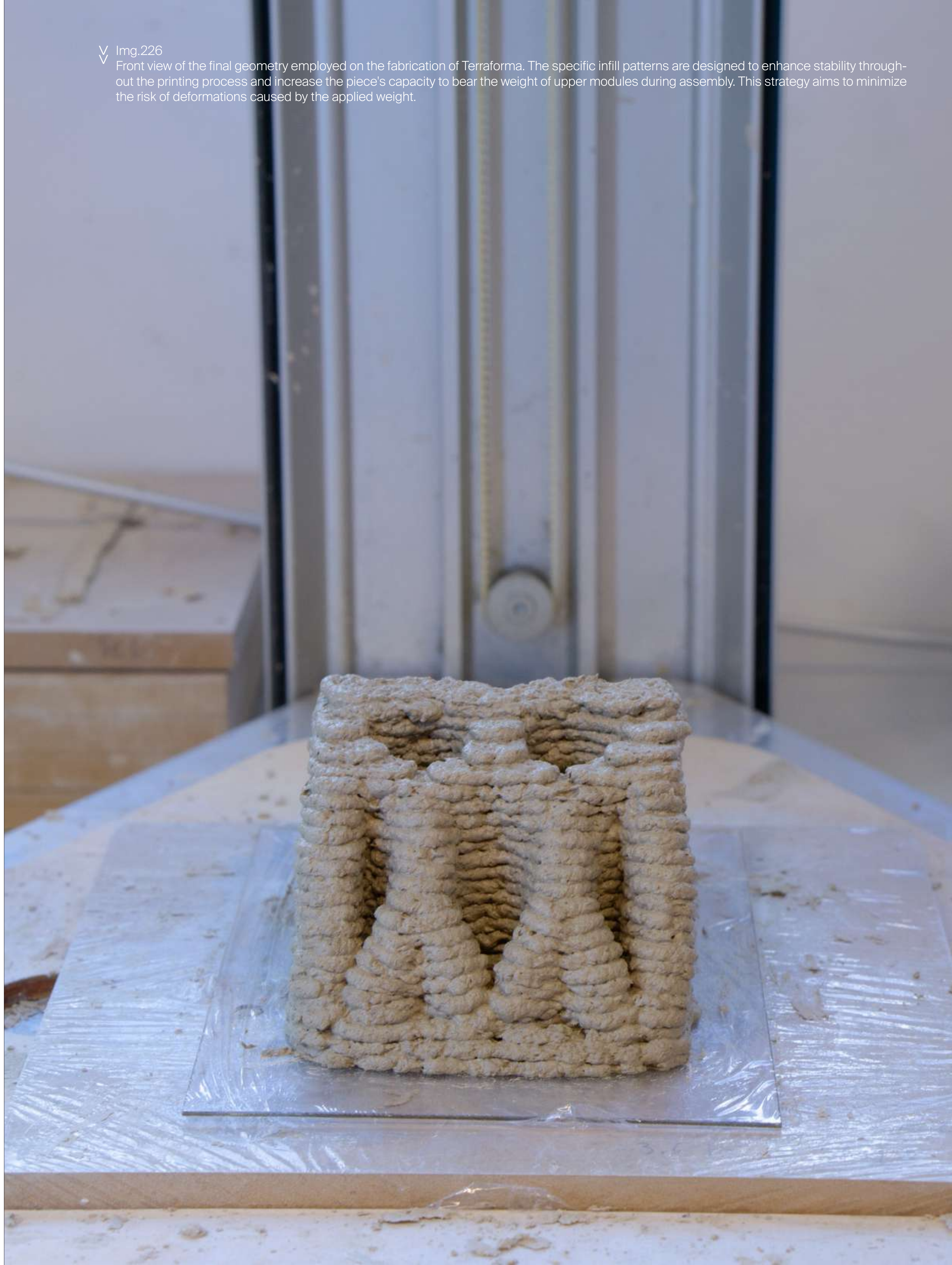


Img.224, 225
3D printing process of the final module geometries employed in the Terraforma fabrication. Modeling and processing phases were conducted considering a theoretical nozzle size smaller than the actual one, facilitating during deposition effective welding of the double walls through overlapping printing paths. Additionally, the modules were vertically scaled to anticipate clay's shrinkage behavior, ensuring circular geometries at the conclusion of the drying phase.

The second strategy involved an intervention on the geometries related to the clay's shrinkage behavior. Based on observations from the last samples and a defined horizontal assembly logic, the pieces were scaled along the Z axis to anticipate material behavior during the drying phase. The final prototype's pieces were fabricated with geometries slightly exceeding a perfect semicircle and scaled by over 8 percent on the vertical axis. This value was determined by measuring the parts at the end of the first growth cycle, accounting for the loss of this percentage due to part arrangement during this stage. The final modules measured 65mm x 100mm on the print base and approximately 70mm in height. This sizing decision aimed to reduce errors during the process by molding smaller parts and achieving a suitable total height for the final object. Each leg was designed to be composed of 12 modules arranged on 6 levels, showcasing a total height of about 40cm. The inaccuracy about the heihg is due to both the shrinkage behaviour of clay and geometrical factors, considering that the 5mm nozzle will produce parts whose molding dimensions will not be the same as those actually designed. Thus, the total number of modules required was 36, accounting for the three legs supporting the artifact.

Regarding the printing process itself, given the success of the protocol in previous tests, the employed mixture involved the inoculation of clay before material deposition, specifically during the ingredient combining stage. The final recipe consisted of clay (50 percent), inoculated sawdust (21.5 percent), water (25 percent), flour (2 percent), and xanthan gum (1.5 percent). This combination resulted in excellent extrudability and precise definition of 2.5-mm layers compared to other tested mixtures. Material deposition occurred continuously, with pressure ranging between 3-4 Bars, dependent on the material's behavior due to variations in substrate particle size. The printing time for individual modules was minimized to 16 minutes, reducing the contamination window. Post-printing, each piece weighed approximately 350 grams, a significant decrease from the ones recorded during experiments with larger modules. This weight reduction proved crucial in addressing collapse issues during assembly, reinforcing the decision to fabricate smaller modules and prioritize organism growth. The custom printing bases, which saw 1mm plastic planes being employed, served a dual purpose. They facilitated part detachment due to material non-porosity and maintained moisture contact to restart growth after horizontal rearrangment for assembly. Customized bases also allowed placing up to five modules in the same box, maximizing carbon dioxide concentration within the confined space. This factor proved to be fundamental in determining consistent growth of the organism.

Once printed, the modules were placed in boxes within a tent to foster mycelium development. The initial growth cycle lasted about 16 days in a controlled environment with humidity and temperature parameters of 85% and 20-23°C, respectively. Temperature fluctuations were due to the terrarium mat's inability to counteract the declining autumn temperatures during the final prototype's realization. Despite this, an exceptional proliferation of mycelium was observed on most pieces during the growth period. Photographic documentation showcases a consistent fungal skin, reaching 1-1.5 mm thickness with the organism still active. This marked a milestone improvement in the growth process, compared to earlier field tests, significantly influenced the handling of pieces during detachment and assembly. The fungal layer provided elasticity and strength, preventing collapse and limiting deformation under the structure's total weight.



Img.226
Front view of the final geometry employed on the fabrication of Terraforma. The specific infill patterns are designed to enhance stability throughout the printing process and increase the piece's capacity to bear the weight of upper modules during assembly. This strategy aims to minimize the risk of deformations caused by the applied weight.

Img.227
Incubation boxes with the final modules employed in Terraforma prototyping. Employing customized printing bases allowed to place up to five pieces per box, with a significant impact on the increase of carbon dioxide saturation of the growth environment.

It is evident that the targeted intervention to address certain issues encountered in the earlier cycle of experiments has positively influenced the outcomes of these initial process steps. Notably, minor adjustments to geometry design and file processing have demonstrated significant impacts, extending their influence to seemingly unrelated aspects of the process. This is exemplified by the combined effect of a more tightly welded infill pattern and increased carbon dioxide accumulation within the growth environment, resulting in more robust growth. Once again, these considerations underscore the challenges of conducting co-design processes with living organisms, particularly when incorporating an additional layer of deepness given by digital fabrication technologies. The subsequent subchapter will delve into how these aspects played a decisive role alongside the formulation of an assembly strategy and a specific structure to address the most challenging issues identified during the testing phase.

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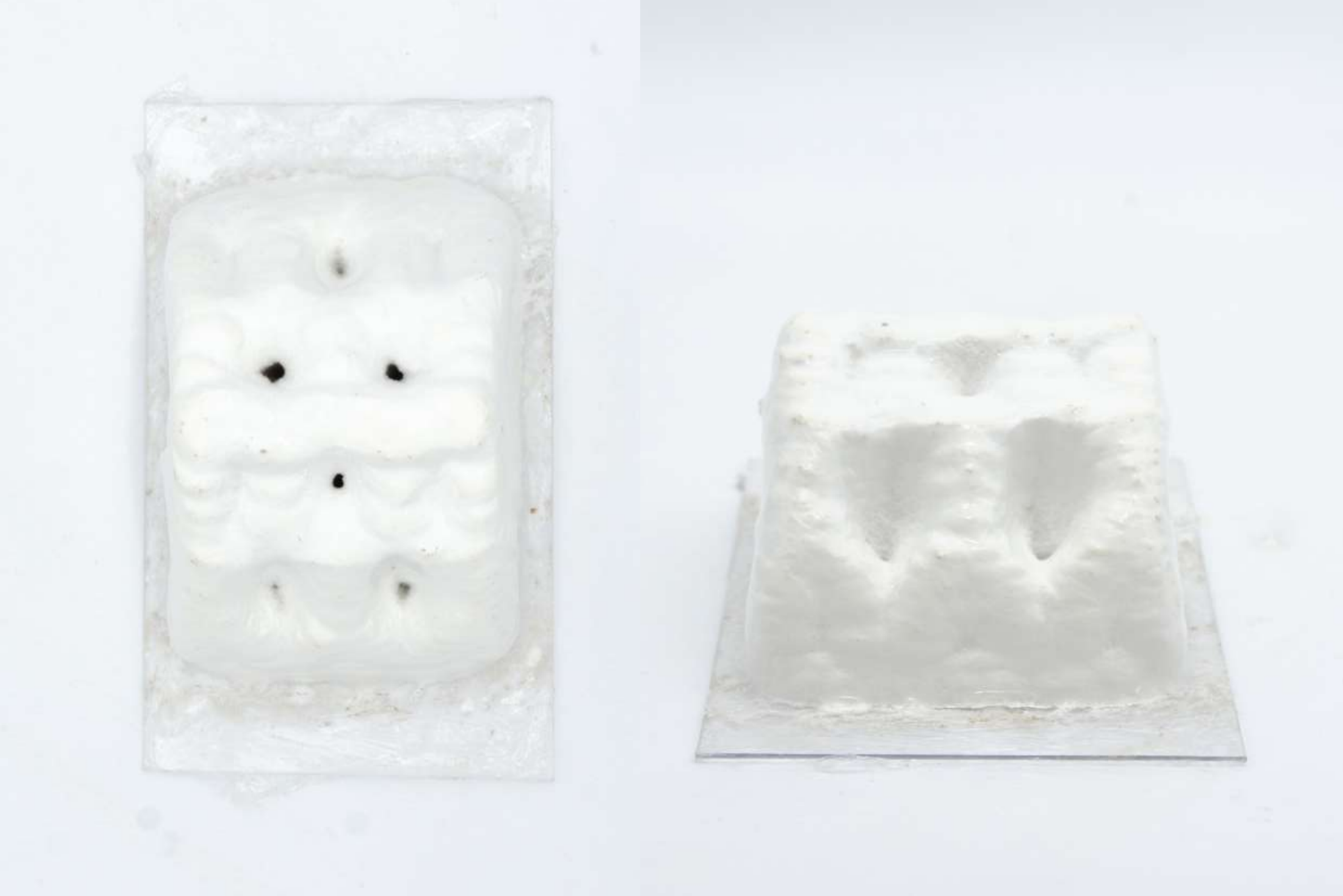
Img.228, 229
Final modules employed in Terraforma prototyping. The fungal matrix demonstrated remarkable consistency, culminating in the formation of a mycelial skin approximately 1-1.5 mm thick by the conclusion of the growth phase.



7.2.2

Assembly strategy and deactivation

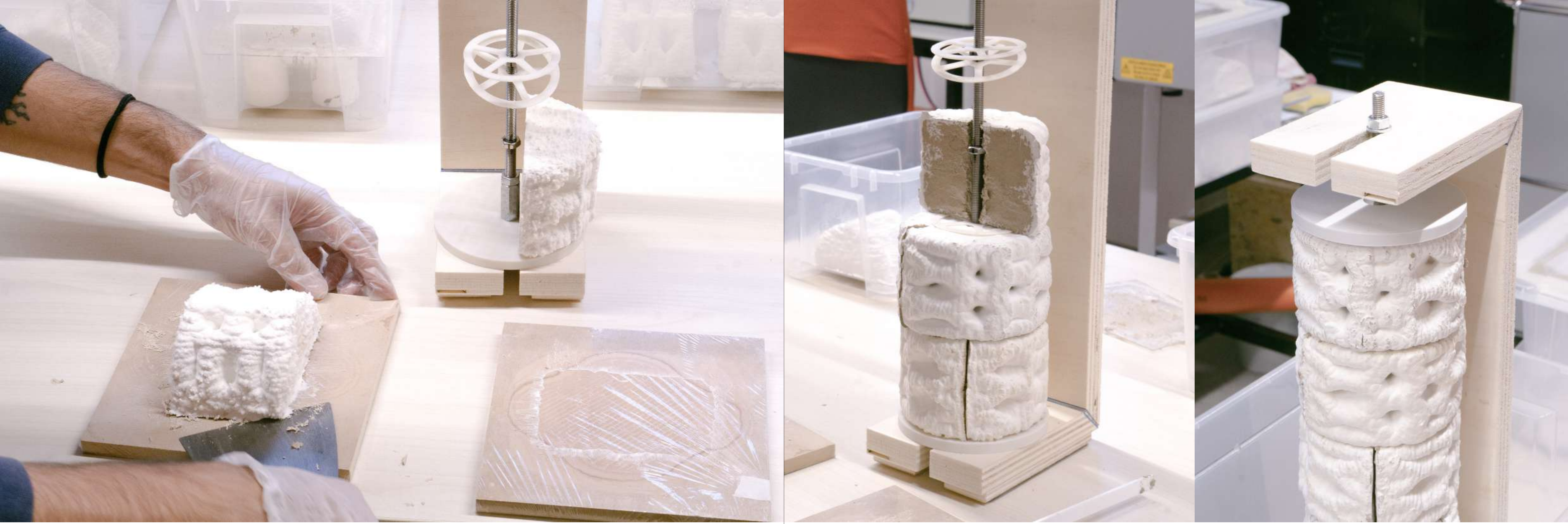
This section is dedicated to elucidating the process of assembling the supporting components of the artifact and deactivating the organism, with the subsequent closing of the pathway that sees the realization of the design phase in collaboration with the living organism. The field investigation phase delved into five segments of the digital fabrication process involving mycelium. These segments encompassed the printing mixture, definition of geometries, growth cycle, drying, and the assembly and deactivation phase. The latter, marking the conclusion of the experimental cycle, emerged as the primary area of interest with evident unresolved issues. It also represented the most delicate phase of the entire material investigation. Despite devising an assembly strategy effective in connecting pieces through a fungal binding matrix, challenges arose in managing the weight and shrinkage of the composite structure. Tests revealed a notable propensity for deformation and collapse, coupled with additional issues of shrinkage and contamination following the thermal deactivation process, particularly in the presence of large artifacts.

During the fabrication of the final prototype, the designed assembly logic necessitated a more advanced strategy to address the deformation of columns within the artifact structure caused by weight. This method involved creating a special structure with third-party elements serving different functionalities. This system played a dual role: facilitating the connection of manufactured clay elements to the rest of the artifact components and contributing to weight distribution and the maintenance of a vertical axis during stacking. The designed structure comprised a plywood frame with a connected threaded steel bar (8mm in diameter). Firmly anchored perpendicular to the ground, this bar held the modular composition in place and served as the attachment point for additional components in the new assembly strategy. Thin PLA discs with a ribbed geometry, similar to those observed in the last sample from previous experiments, were added to the threaded bar during the assembly of the frame. Unlike those employed in "Clay and sawdust semicylinders sample 3," these discs were characterized by a smaller thickness of 1.5mm and a diameter of 60mm to minimize their impact on the bio-welding process. In contrast to the previous assembly methodology, where vertical assembly followed the module-nut-disc sequence, the nut was placed on the threaded rod, taking into account the maximum shrinkage, during the fabrication of the frame. The clay modules were then stacked with the nut inside them, and the disc was subsequently placed upper of the cylindrical level. This assembly strategy was based on the assumption that, with the progressive increase in weight, the compression of modules would cause the descent of the discs in each level. However, once they met the nut in place, they would have halt their descent, supporting the weight of the respective upper level.

Img.230, 231
The support framework employed to assemble the coffee table legs incorporated a strategic approach that included functional elements. These elements such as 3D printed disks, a threaded bar and nuts, were implemented to ensure proper weight distribution and prepare the column to be connected with other components of the artifact.

A 3-cm-long nut positioned on the lower part of the structure facilitated the placement of a feature on the bar designed to connect the legs to the support surface of the artifact. Specifically, the threaded bar was jointed to this feature for half of its length, allowing space for an additional threaded feature to attach to the nut. Since this component was functional for mounting the legs with the top of the object, it was obviously necessary for it to be present on the top of the legs to be made instead of on the bottom. However, the opposite choice of placing it on the bottom of the frame follows a very specific reason related to the shrinkage behavior of the material. Placing the feature at the bottom ensured that, regardless of the height difference resulting from the shrinkage of the modules, the drying phase would not affect the final position of this feature. The legs of the artifact were then assembled upside down in relation to their ultimate orientation. To prevent contact between the modules and the wooden frame, and to address potential contamination issues arising from the high humidity of the growth chamber, two additional functional PLA elements were fabricated. These elements also served for column manipulation during removal from the frame and provided support during deactivation.

Once the frame for assembly was fabricated, the artifacts were composed following the customary logic of tipping and staggering the pieces. It was nec-



^ Img.232, 233, 234
Stacking the modules during fabrication of one of the Terraforma legs. The assembly phase was carried out using the specific framework designed to control the weight distribution of the pieces and prevent deformations.

Img.235
Front view of the assembly support framework with stacked modules right before undergoing the second growth cycle.

essary to remove a portion of material near the area in contact with the threaded bar to ensure a better fit between the halves of each level. Pieces with greater firmness, attributed to a combination of factors such as fungal skin development and drying of the clay matrix, were placed at the bottom. The impact of fungal matrix development on the piece's ability to support greater weight by exhibiting an elastic behaviour, was more pronounced than the factor related to the drying process. The progressively staggered arrangement of modules during vertical stacking contributed to the texturization of the composition in its wholeness, simulating a revolution in the infill pattern of the geometries. The assembly strategy, supported by the extended growth time the pieces underwent, effectively prevented deformation and collapse of the artifacts during connection, even under high weight loading.

After assembling all twelve modules, the frame incorporating the column was placed into larger containers and underwent a subsequent growth cycle to promote further growth and develop the bio-welding between the layers. This growth phase extended for an additional seven days, during which the organism resumed growth, generating new filamentous material observable on the artifact's surface. This proliferation not only formed a binding matrix between layers but also encouraged the growth of fungal material between respective halves, ensuring robust final adhesion among all the pieces. Following the second growth period, the artifact was extracted from the frame and subjected to the deactivation process. This step maintained the upside-down orientation to avoid any positional loss of the components connected to the threaded rod, especially crucial during this phase. Deactivation occurred through a thermal cycle lasting two and a half hours, with the maximum temperature of 100°C gradually reached after an hour and a half before being held constant. After turning off the oven, it returned to room temperature after an additional hour, and only then were the structures extracted. This departure from previous experiments on large artifacts was driven by concerns about post-firing contamination due to high residual moisture. The chosen thermal profile aimed to pre-dry the material before actual deactivation at the maximum temperature, with residual kiln heat helping stabilize the artifact's moisture content.

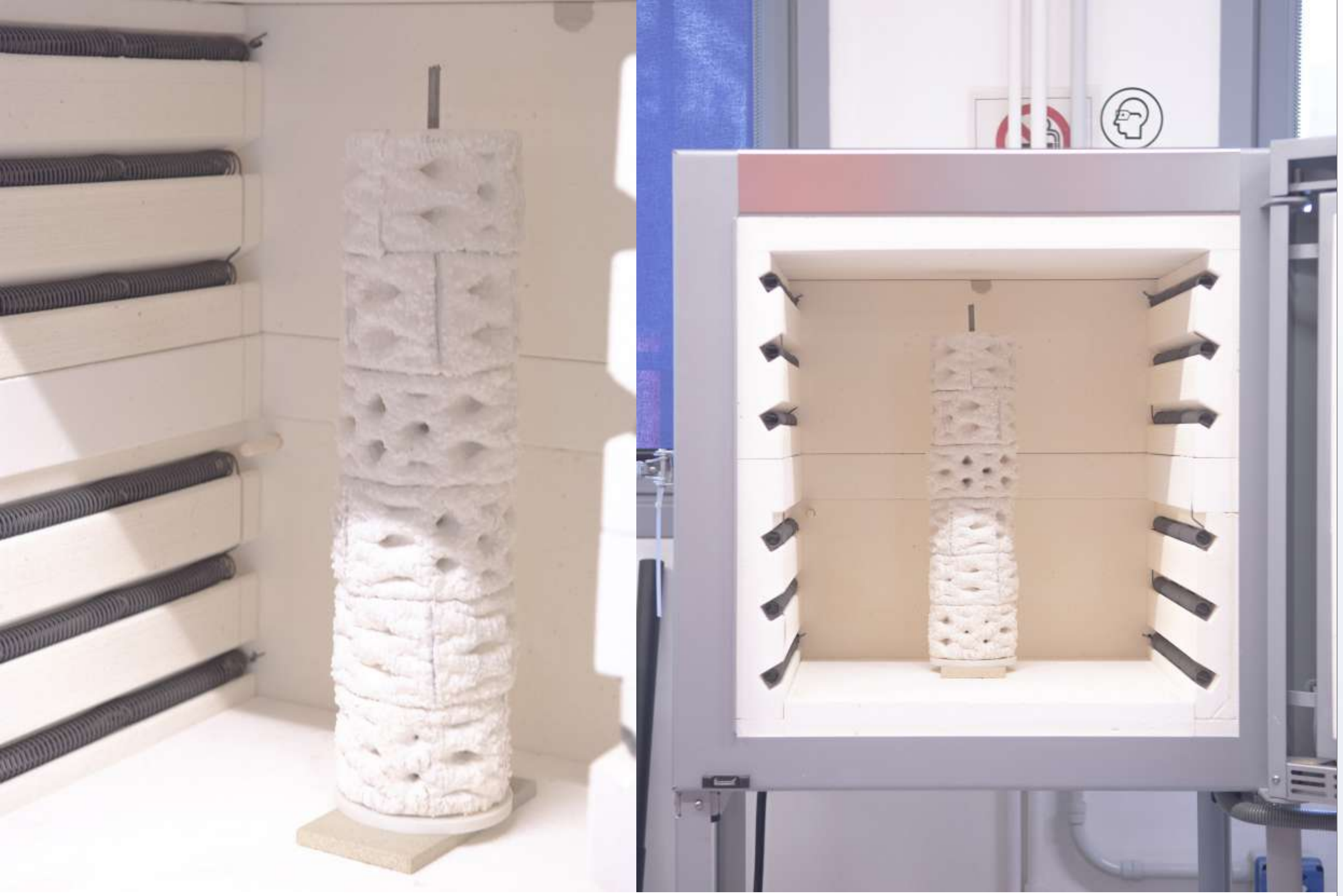
However, after the baking process, a greater dimensional shrinkage than anticipated was observed causing some of the layers to detach from each other. This resulted from the support disk reaching the nut which prevented the PLA component to further accompany the descent of the modules. This issue led to the failure of the nut-disc system in relation to the heat treatment process, despite its effectiveness during the assembly of still-wet parts. Nevertheless, having validated the threaded rod's suitability for managing on-axis weight distribution and preventing lateral collapse, two additional assembly strategies were employed with the same principle. One involved still using PLA disks but removing the nuts, while the other contemplated direct stacking of modules without external elements. Both strategies required an extended growth period of 25 days to allow the pieces to dry and gain rigidity. The longer time did not impact the quality of the fungal matrix, which exhibited similar thicknesses as in a 16-day cycle. At the end of the first growth cycle, both strategies— one with discs and one without—were applied to connect the pieces. In both cases, an additional seven-day incubation period followed the second phase of organism proliferation. After heat treatment using the same parameters as the previous structure, the mycelium was deactivated, and the legs sufficiently dried, resulting in solid bio-welding between the levels of the artifact. This process yielded a single body, seamlessly assembled from the twelve modules.

In relation to this, it can be inferred that, although the utilization of PLA discs positively contributed to weight distribution during assembly, it was not an essential variation for the envisioned connection strategy. Generally, direct contact between colonized surfaces is preferable when dealing with sufficiently rigid and dry assemblies, as it is directly linked to the development of a firmer and more advanced bonding matrix. An intervention during the growth phase, coupled with an extended period of organism proliferation and a tilting of the pieces to promote growth on all surfaces, proved to be a sufficiently effective protocol for obtaining modules robust enough to bear the weight of the assembled structure. Consequently, the three legs required for the prototype were crafted according to this approach, adopting a final assembly strategy that omitted any PLA ribbed elements.

The outcome consisted of three solid structures in the hybrid material, achieved through an assembly stage meticulously designed and executed based on the organism's metabolic qualities. The dried columns fabricated had a height of approximately 370mm and a diameter of about 90mm, resulting from the drying process and shrinking from initial values of 420mm and 110mm. The variance between the dimensions resulting from the assembly of wet pieces and the mathematical sum using the stated dimensions of individual modules can be attributed to the difference between the actual printing nozzle used and the theoretical principles on which the files were modeled and processed. Additionally, the fabricated pieces incorporated connection elements within them, prepared for the subsequent assembly stage with the remaining components of the final artifact.

Img.236
View of the growth chamber with the assembled column and the single modules undergoing the second and first growth cycles, respectively.

Img.237, 238, 239
Close-up and on-framework views of the assembled leg at the end of the second growth cycle. The extended growth period played a crucial role in restarting the organism's growth and enabling the bio-welding process to occur between the individual modules and levels.



^ Img.240, 241
Views of the assembled artifact removed from the support framework and ready to undergo the thermal deactivation process.

v Img.242
Front view of the piece after the thermal deactivation process.

Img.243, 244
Close-up view of the thick fungal skin covering the surface of the pieces.

Img.245
Close-up view of the thick fungal skin covering the surface of the pieces..

7.2.3

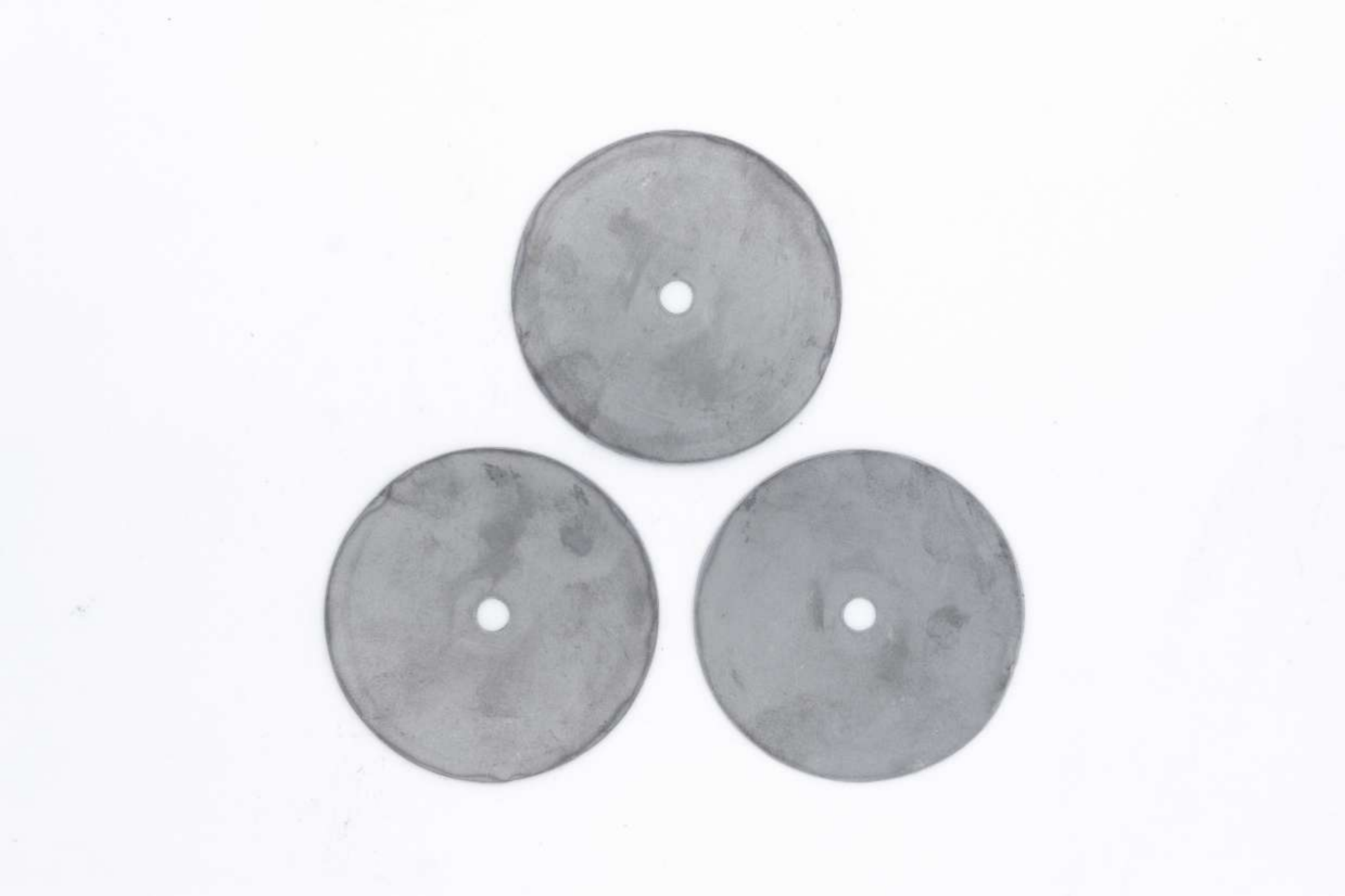
Third party components and final assembly

The concluding segment of Terraforma's prototyping journey details the design solutions applied to the fabrication of third party components and the general assembly of the artifact, incorporating the legs crafted from the material central to the investigation work. In the process of the object typology definition, it was anticipated how the fabrication of structural elements involved integrating preparatory features for subsequent connection with other components of the coffee table, specifically a base and a tabletop.

Regarding the inclusion of a bottom, two primary reasons influenced this decision. Firstly, there was a necessity to create a support element from the ground distinct from the clay material, which, despite its rigidity, is susceptible to relative fragility that could lead to deterioration, especially with the potential risk of impact and abrasion during use. Secondly, since achieving perfectly flat support surfaces cannot be guaranteed after manufacturing and drying, the base serves as a means to ensure the artifact's stability during use. Creating a unified metal base for the three legs proved to be a functional method to enhance the table's stability. The piece, crafted from a two-mm thick sheet metal with 8mm holes arranged radially at 120mm to the center of the object, facilitated alignment of structures in the hybrid material with the base by exploited the threaded rod. Adjustable feet were then affixed to the bottom, ensuring stable ground support and enabling micro-adjustments on uneven surfaces. These feet, obtained through FDM molding of cylindrical geometries with an internal hole accommodating an 8mm inner diameter bushing, guaranteed stable ground support and allowed for micro-adjustments on imperfectly flat surfaces. The assembly of lower components was designed by leveraging inserts and threaded elements as pivotal components, crucial for maintaining structure alignment during assembly.

These threaded elements were equally crucial for connections with the upper components of the artifact—the support plane and additional levelers. Factors influencing the final height of individual legs included printing pressure parameters, material deposition precision, material shrinkage vertically and horizontally after connection, slight deformations during handling and assembly, vertical compression during leg assembly on the frame, and final shrinkage during the organism's thermal deactivation process. Given the numerous variables leading to changes in module volume and considering that the leg comprises twelve of these elements, expecting absolutely identical heights for the three artifacts at the process's end is nearly unrealistic. Despite this, meticulous adherence to design protocols resulted in obtaining three elements with height differences within a range of less than one cm. Despite the minute difference considering all variables, third-party components were integrated to level the support point of the tabletop on the legs. These elements, also fabricated through FDM additive technologies, featured specific heights, fitting into threaded inserts atop the columns to bring the tabletop's contact point to a uniform height. These elements were then concealed with metal discs made from the same sheet metal as the base, enhancing the contact surface between the plane and the levelling features and creating a textural transition between the top and bottom. The assembly of Terraforma was completed with a tempered glass top, finally secured to the threaded features in the coffee table's legs using screws.

^
^ Img.246, 247
On the left page top view of the metal base employed in the assembly of Terraforma. On the right the 3D printed leveling feet featuring threaded inserts, designed to allow micro-adjustments and ensure the stability of the artifact.



^^ Img.248, 249
On the left page top view of the metal disks employed to enhance the contact surface between the plane and the leveling features. On the right the 3D-printed elements featured specific heights, fitting into threaded inserts atop the columns to bring the tabletop's contact point to a uniform height.

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Terraforma, front and top view.

Img.252, 253
Terraforma, bottom base detail and front view.

Img.254, 255
Terraforma, glass plane detail and front view.

Img.256, 257
Terraforma, glass plane details.

Img.258, 259
Terraforma, detail of upper connections between the legs, disks, and glass.

^ Img.260, 261
^ Terraforma, comparison with human scale and top view.

Img.262, 263, 264, 265
Terraforma, details of legs and glass plane.

^ Img.266, 267
^ Terraforma, top views.

Img.268
Terraforma, front view.

CONCLUSIONS AND FUTURE PERSPECTIVES

Following the final phase that saw the materialization of the material investigation through the fabrication of the physical output Terraforma, the research comes to an end and we proceed to draw reflections on the results obtained in relation to the stated project objectives and the design process used. Throughout the research, a cognitive exploration of the materials, especially the mycelium organism, was undertaken. This challenging journey led to the development of a specific design methodology and innovative operational protocols. The primary goal of the research was to delve into the material potential, particularly within the realm of products, emerging from the intersection of seemingly incongruent domains—clay materials and fungal materials. The decision to embark on this specific path was driven by the aspiration to explore diverse approaches in design, transforming it into a catalyst for social change and initiating new circular dynamics rooted in an alternative understanding of natural resource utilization.

At the conclusion of this investigation, noteworthy contributions within the biomaterials domain come to light, significantly expanding scientific knowledge concerning fungal materials and their associated processes. In particular, the work in question is proposed as one of the first ever to address the issue of compatibility between them and an inert material such as clay. In this regard, it is stressed that the knowledge gap that emerged during the preparatory phase of the project has been at least partially filled through the writing of this thesis research. While previous authors had touched upon the uncharted territory of this intersection, their results and level of investigation remained relatively superficial. This circumstance left the potential of the hybrid material and the design practices essential for its cultivation ambiguously defined. Terraforma stepped into this context, aiming to offer insights into drafting protocols and defining design logics in full collaboration with the mycelium organism. Specifically, all the main objectives stated prior to the start of the field phase can be considered achieved.

Firstly, the methodology employed in the fabrication of the produced samples and the final artifact illustrated the potential harmonization of digital fabrication technologies with the early-stage inoculation of materials by the mycelium. This research stands out as the first to showcase the deposition of an already inoculated mixture, introducing a standalone design approach not observed in prior studies on similar topics. This innovation significantly reduced the necessity for secondary activities related to the inoculation of printed artifacts, such as filling and subsequent autoclave sterilization. The development of an inoculation protocol operating under semi-sterile conditions also liberated geometries from formal constraints tied to manual filling requirements. Regarding the timing of inoculation during the process, alternative approaches were explored in the research. These included testing methods to sterilize artifacts through more accessible means than laboratory equipment or subjecting the mixture to an additional growth cycle before deposition. While the results obtained were not entirely satisfactory for concluding the research positively, they nonetheless provide a valuable contribution to the broader practical scenario.

Secondly, it is pertinent to reflect on the specific material characteristics achieved by establishing clear and repeatable cultivation and fabrication protocols. Notably, the hybrid material obtained at the end of the thesis work exhibited a level of fungal matrix growth unprecedented in its intersection with clay. This dual achievement contributed to verifying the compatibility between the two materials and yielded a higher level of output compared to previous research efforts, with properties comparable to those of MBCs. While acknowledging the inherent differences between the materials, the attainment of such a high-quality fungal skin coating opens up novel usage scenarios that may be explored by other researchers interested in further investigating this material.

Furthermore, the material derived from the ultimate recipe, utilized in the final prototyping phase of Terraforma, displayed outstanding mechanical and physical properties. These qualities, in conjunction with a comprehensive evaluation of the entire process, played a pivotal role in determining the nature of the artifact to be crafted at the culmination of the research. Despite the absence of empirical testing to quantify values in comparison to a greenware clay-only equivalent, it can be asserted that the novel hybrid material demonstrates a noticeable enhancement in its mechanical behavior. A direct comparison with traditional UBWCCs reveals an immediate advantage, as the fungal layer formed on the surface addresses critical issues related to water contact, a concern highlighted during the research phase of these materials.

Simultaneously, owing to the absence of specific thermal processes within the defined design protocols, the material assures complete biodegradability at the conclusion of its life cycle. The research, based on an optimal recipe comprising all-natural ingredients such as clay, sawdust, water, flour, and xanthan gum, introduces a new sustainable material with potential applications as a substitute for ceramics in specific contexts. The fabrication process, observed in both the samples from the field investigation phase and the structural components of the final prototype, aligns with principles of circularity. Additionally, it envisions a future where resources can be recovered and reused, at least partially, upstream in the production process. This stands in contrast to a primary challenge identified in the research related to the transformation of clay into ceramics, wherein the loss of pseudo-coherent behavior post-firing designates ceramics as a non-renewable and only partially sustainable material. Significantly, the positive impact extends to a drastic reduction in emissions from the process. Eliminating two thermal cycles to obtain the hybrid material, albeit with performance distinctions, results in a product as solid and water-repellent as a glazed ceramic, marking a noteworthy environmental footprint reduction achievement.

Ultimately, the creation of Terraforma serves as a compelling illustration of a design practice entirely centered on enhancing the properties of mycelium. The generation of an artifact exceeding the size achievable with existing instrumentation, achieved through synergy with the organism's metabolic processes, reshapes a context in which design collaboration with living organisms triumphs over limitations imposed by production means. In this research, the efficacy of the fungal matrix in facilitating the bonding of different components, even within a hybrid material of clay and mycelium, was demonstrated. The adopted design approach, blending Material Driven Design (MDD), Digital Biofabrication, and DIY, narrates an exploratory journey wherein the co-design of human, mycelium, and machine becomes the means to fulfill design goals and requirements. The mutual shaping process between the material and the designer, influenced by the manufacturing technologies involved, highlights how both constraints and opportunities contribute to the decision-making.

As we conclude this exploration, contemplation arises regarding potential future expressions. Numerous avenues remain open and viable for further development in exploration and project realization. Given the novelty of the researched topic, the limited available literature compelled the formulation of a design approach based on novel operational protocols, representing an immature approach to hybrid material. While this limitation constrained the research and final output development, relying mostly on the author's firsthand knowledge, the experimental stage of the research paves an innovative path for fungal materials. As more advanced knowledge on the subject emerges, the scenario unfolds for validating the compatibility between these material areas, leading to undiscovered applications in the realm of product design.

In relation to this, it would be intriguing to explore alternative assembly processes that embrace different principles than those employed in the current thesis. This specific domain not only emerged as the most critical in the personal exploratory journey but also represents the most delicate aspect on a broader scale. It is intricately linked to numerous variables such as structural weight, contamination risks, and the actual realization of bio-welding between the components to be connected. While the solutions devised during the implementation of Terraforma gain value within the analyzed context and the adopted methodology, they are not intended as universal, despite the design of implementation protocols to ensure replicability. Therefore, there is room for investigation to intervene in different segments of the process, providing guidelines that have proven effective, and exploring variables of success and failure.

Another potentially interesting aspect is the hypothetical testing of an alternative deactivation process to thermal cycles. The research explicitly revealed how treatments involving temperature result in the definitive deactivation of the organism, as opposed to methods based on humidity that induce organism hibernation, allowing for potential reactivation within certain intervals. In this context, a possible alternative method could involve prolonged exposure of the organism to low humidity, facilitating atmospheric drying of the clay matrix. This approach, although causing slower drying compared to a kiln, would ensure controlled drying. However, it exposes the organism to contamination risks during vulnerable periods when it is no longer in a vigorous state. Such a hypothetical deactivation method would require a sterile environment and appropriate laboratory equipment. While this potential development was hypothesized but not tested due to space constraints in the research setting, it could serve as an effective deactivation methodology to address some of the critical shrinkage issues identified during experimentation.

Lastly, potential research progress could center on empirically evaluating the outcomes attained through a series of tests aimed at assessing the enhancement in the material's behavior resulting from the organism's proliferation. These tests might encompass measurements of mechanical and physical qualities, with a specific focus on analyzing the hybrid material's response to water contact. Additionally, other tests could concentrate on appraising the bonding strength facilitated by the formation of a fungal matrix during bio-welding processes.

Terraforma aimed to trace a path toward achieving new forms of progress, understood as a detachment from blind anthropocentric dynamics in favor of a reconnection with the inherent natural order to which our species belongs and is inseparably tied. The vision contained within the thesis work thus opposes the conventionally understood concept of evolution, first by theorizing and subsequently by demonstrating that an effective change of perspective to be accomplished through reconciliation with the ecosystem and living beings is truly viable. In this scenario, the value of the design practices by which we shape the world we inhabit takes on a fundamental role, putting us once and for all in front of a choice oriented toward either a departure from our intrinsic nature or from what we currently represent in the balances of the ecosystem we inhabit. Terraforma tells of a possible new reality to be imagined, before even on other distant worlds, on our own planet.

IMAGE CREDITS

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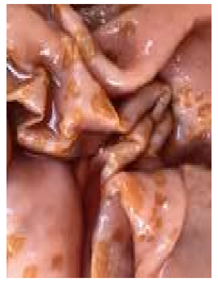

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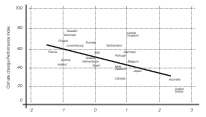

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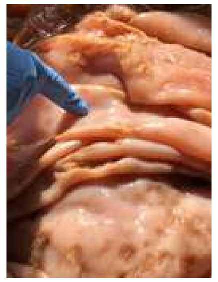

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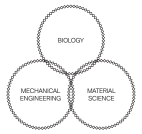

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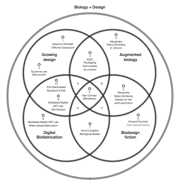

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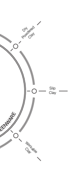

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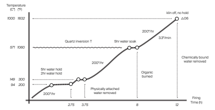

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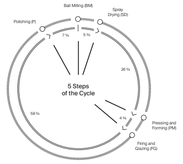

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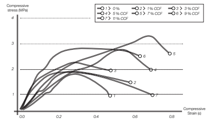

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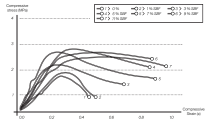

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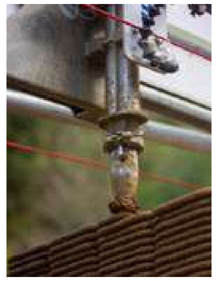

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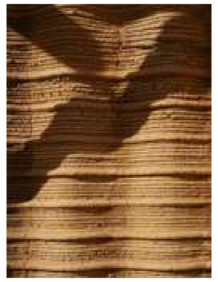

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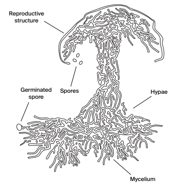

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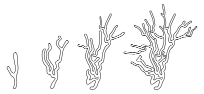

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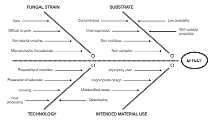

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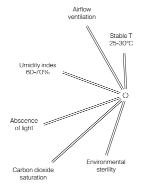

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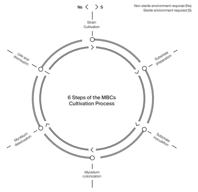

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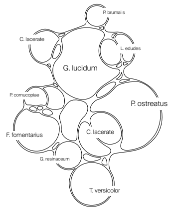

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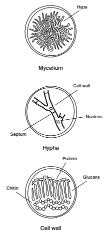

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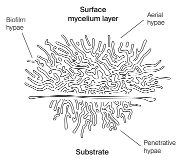

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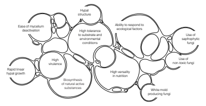

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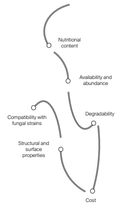

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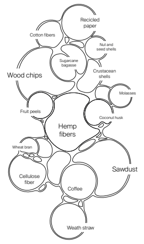

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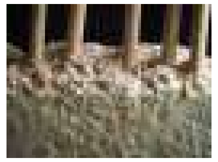

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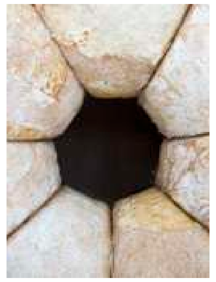

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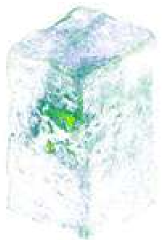

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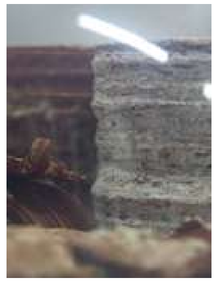

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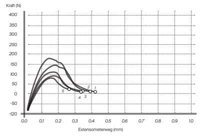

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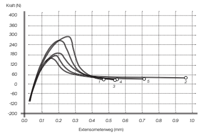

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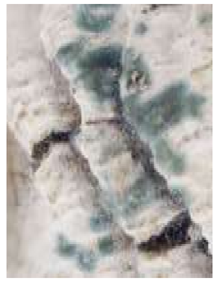

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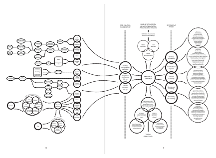

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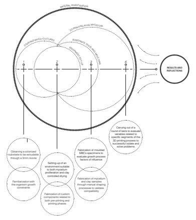

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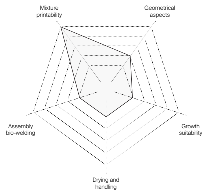

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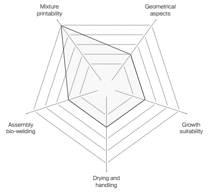

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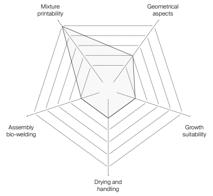

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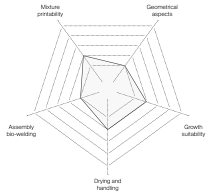

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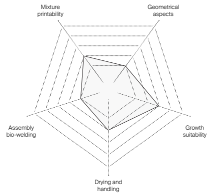

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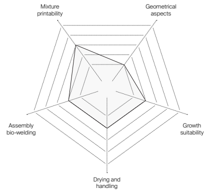

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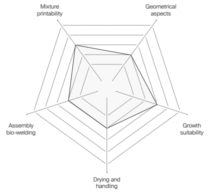

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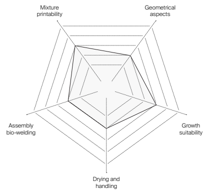

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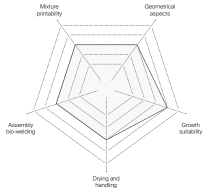

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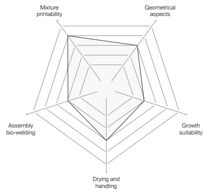

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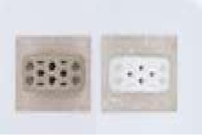

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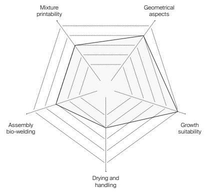

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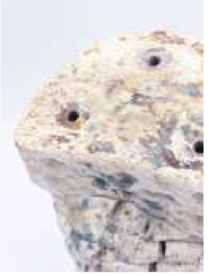

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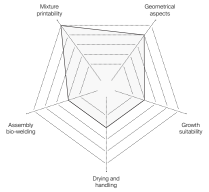

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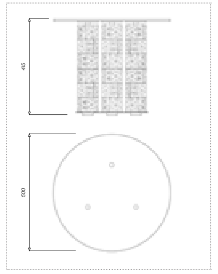

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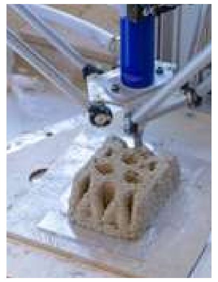

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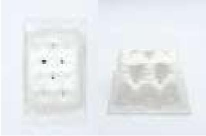

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TERRAFORMA

Material investigation on the possibilities to combine natural growth of mycelium and unfired clay for novel sustainable product design applications

Supervisor
Patrizia Bolzan

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Master thesis in Integrated Product Design
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