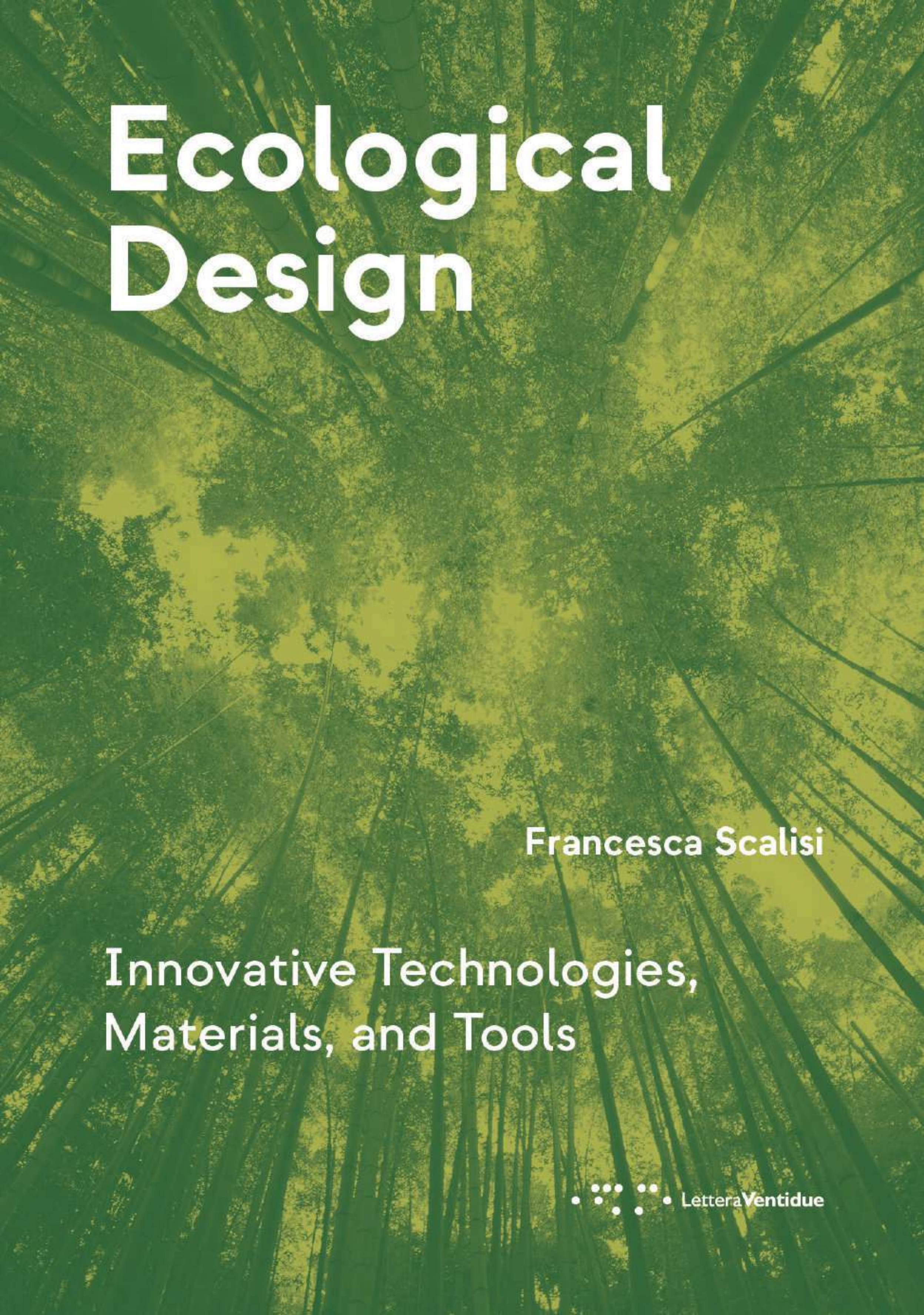

Ecological Design

Francesca Scalisi

Innovative Technologies, Materials, and Tools

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Introduction

In the transition from the Anthropocene to climate neutrality, it is not enough to "design better": we need to measure, decide, prototype and regulate in a manner consistent with Agenda 2030 and with European programmes that have redefined criteria and priorities – from the Green Deal to the Renovation Wave, from the Circular Economy Action Plan to the New European Bauhaus – orienting policies, supply chains and markets towards scenarios of decarbonisation, circularity and social well-being. In this context, design acts as a cultural and technical infrastructure that connects material research, production processes and technical choices, transforming principles into operational specifications and public value.

Ecological innovation is only a matter of design if it is made legible by shared assessment tools throughout the entire life cycle. For this reason, Environmental Product Declarations (EPDs) are considered a design lens, not a compliance requirement: they provide comparable data on energy and impacts, enabling informed choices in material selection, provided that system boundaries and usage assumptions are made explicit. The volume shows how these devices – already integrated into protocols and rating systems – can become drivers of design and the market, stimulating transparency, performance competition and supply chain innovation.

In addition to metrics, workflows are also critical. Contemporary design works "with" data: BIM, parametric models, and digital production enable construction specifications, performance scenarios, and material traceability to be derived from the design, thus reducing errors and anticipating interference. This digital infrastructure is not a technological fad: it is a prerequisite for linking measurement and production and for integrating circular-economy criteria (disassembly, recyclability, bio-based content) into decisions on form and detail.

This is the basis for the volume's structure: from measurement to implementation to regeneration. The starting point is the critical use of environmental product declarations (EPDs) in the choice of materials; this is followed by digital tools that translate metrics into products; bio-based supply chains and timber construction methods are examined; phase change materials (PCMs) for low-energy thermal regulation are analysed; nanotechnologies are discussed as cross-cutting facilitators (durability, surface selectivity, reduction of maintenance cycles); and finally, clay and nano-innovation are examined as a paradigm of "low-impact/high-performance" hybridisation, which enhances local resources and construction knowledge. The aim is not to collect "novelties", but to show how design builds bridges between scientific knowledge, standards, tools and practices, generating reproducible solutions on multiple levels, from materials to components, from buildings to landscapes, with modes of intervention ranging from the conceptual-methodological to the design-oriented, from the regulatory-educational to the technological-experimental.

This framework includes the assessment matrix (scales, types of action, Sustainable Development Goals) that will be used to compare cases and, above all, to highlight transferability and impact: from EPD criteria in public procurement to mix-design choices for innovative materials, to the integration of digital tools that make every decision traceable and assessable. In short, design drives innovation when it can demonstrate, with data and prototypes, "why" a solution is environmentally friendly, "where" it produces benefits and "how" it can be replicated in other contexts.

The volume offers the research community, professionals, and administrations an operational framework in which materials, technologies, and tools are not isolated ingredients but parts of a measurable design process capable of contributing – quickly and with evidence – to achieving the Sustainable Development Goals (SDGs). In the process, the scales (from materials to landscape) and types of action (from conceptual hypothesis to standard, from prototype to specification) change, but the traceability of decisions remains constant. Every choice must be justified in terms of environmental impact, technical performance, life-cycle costs and alignment with the SDGs. This framework, which we will use to read the contributions, allows us to avoid two mirror-image errors: on the one hand, the aestheticisation of ecology ("green" materials without numbers); on the other, the bureaucratisation of innovation (metrics without design). The expected result is a design capable of driving innovation: curious in opening up possibilities, rigorous in testing them, and responsible in institutionalising them.

The volume opens by outlining the cultural and political framework within which ecological design operates: from the environmental awareness that has gradually permeated the design disciplines to the most recent international agendas and European programmes. It clarifies why talking about technologies, materials, and tools today means taking on a mandate of public responsibility, in which co-benefits and compromises must be made explicit and negotiated.

The second translates the framework into operational metrics. LCA and EPD help select materials and write specifications consistent with circularity and decarbonisation. Cautions emerge – system boundaries, data quality, often-overlooked stages of use and end of life – but above all, the possibility of translating numbers into decisions, transforming transparency into a competitive lever, and fostering a shared culture.

The third chapter shows how data becomes artefacts. Parametric modelling, BIM information environments and digital manufacturing create a circuit between hypothesis, simulation and prototype; errors are anticipated, interferences are resolved before construction, and the traceability of choices is consolidated. Here, we understand that talking about tools is not technology for its own sake: it is the condition for making what metrics make desirable, implementable, and scalable.

The fourth chapter addresses wood as a key material in the transition. It highlights the advantages (carbon sequestration, prefabrication, speed) along with open questions (adhesives, joints, performance requirements), with a particular focus on the second life of components. Wood thus becomes a testing ground for circularity: designing does not just mean choosing a renewable material, but also creating the conditions for it to be dismantled, reused and put back into circulation without losing value.

The fifth chapter deals with passive-dynamic systems and introduces phase change materials (PCMs) for microclimate control capable of mitigating heat peaks without increasing the number of systems and complexity, and of communicating with digital tools that optimise configurations.

Finally, the sixth chapter addresses the topic of raw earth enhanced by nanotechnology: natural additives and "green" nanotechnologies improve resistance and durability while preserving low embodied energy and strengthening local supply chains and construction knowledge. It is an example of intelligent hybridisation between low-tech and high-tech, where innovation does not erase the material's identity but makes it usable in contemporary contexts.

The path outlined in the volume – measuring, manufacturing, bio-constructing, optimising, enabling, regenerating – restores design's role as the "director" of ecological innovation: a director who combines knowledge of materials, digital infrastructures, life-cycle metrics, and the ability to institutionalise solutions through standards, specifications, and purchasing policies. A double convergence emerges from the contributions. On the one hand, a methodological convergence: each proposal is accompanied by indicators, usage scenarios and replication conditions, so that the design value is not merely stated but demonstrated. On the other hand, there is operational convergence: innovations reinforce each other – LCA/EPD inform parametric and BIM workflows; these make it possible to calculate the choice between wood, PCM and nano treatments; the combination with local supply chains (raw earth) reduces environmental and social impacts on the scale of the building and the territory.

For the scientific design community, this means, first and foremost, consolidating a research agenda that weaves links among materials science, process engineering, and regulatory studies to produce shared evidence and transferable design knowledge. The first perspective, therefore, concerns the datafication of materials ecology: EPDs and LCAs in machine-readable format, natively integrated into BIM environments and parametric models; material libraries with explicit system boundaries and comparable end-of-life scenarios; material passports and digital product passports linked to environmental, performance and economic metrics throughout the life cycle.

A second perspective concerns biomaterials and reversible construction systems. The maturity of structural timber requires research to shift towards removable joints, bio-based adhesives and adhesive-free configurations that simplify end-of-life. The case of raw earth enhanced with natural additives and clay nanotubes shows how low- and high-tech hybridisation can keep embodied energy low while raising mechanical and hygrothermal thresholds. Here, research aims to establish standards and guidelines for businesses and public administrations to make the local supply chain scalable. In all these directions, the guiding principle remains reversibility: dismantle, repair and reuse before recycling.

A third perspective concerns passive-dynamic systems and microclimate control. PCMs are effective when adapted to the climate and intended use, and when placed in layers designed using energy calculations. The aim is to create passive adaptive envelopes, in which parametric design governs inertia and ventilation, and in which *in situ* monitoring feeds digital twins of buildings and neighbourhoods to verify the delta between expected and actual performance. Here, research should produce shared testing methods, open datasets, and commissioning protocols that enable comparable assessments across different solutions.

A fourth perspective concerns responsible nanotechnologies. Nano-solutions are more of an enabler than a category in themselves: safe-by-design protocols, comprehensive LCAs and risk management procedures throughout production, installation and end of life are needed. The expected scientific impact lies in standardisation: comparable methods, traceability, interoperable databases. Only in this way will the promise of efficiency not translate into upstream environmental costs or end-of-life criticalities.

The volume, therefore, outlines a common lexicon between research and practice, which allows, first, experimental results on materials and components to become project specifications and market rules; second, it outlines a methodological platform that makes heterogeneous contributions comparable and accelerates their transferability across scales – material, component, building, city – and across types of action – from conceptual to regulatory. Finally, it outlines a concrete contribution to the achievement of the SDGs (in particular SDG 6 – Water; SDG 7 – Energy; SDG 9 – Industry, Innovation, and Infrastructure; SDG 11 – Sustainable cities and communities; SDG 12 – Responsible consumption and production, and SDG 13 – Climate action), because each choice is conceived as a node in a network of co-benefits and declared compromises. Ultimately, the volume does not deliver a catalogue of technologies, materials and tools, but an operational framework for using Design as a "decision-making infrastructure" in the ecological transition, with the intention of inviting the scientific community to make Design the place where environmental innovation becomes shared knowledge, public decision-making and quality of the inhabited space.

1. Evolution of Ecological Thinking and Sustainability Policies

A Reference Framework for Ecological Design

To implement possible thoughts on complex human processes and mitigate environmental effects that characterize our era, it seems appropriate to outline the reference framework by retracing the steps that have marked not only the evolution of the 'ecological' thought but also the current policies, the strategies and approaches theorized to face the polycrisis ahead. The awareness that uncontrolled human activity generates irreversible consequences for the environmental impact on our planet is not recent but can be dated to the beginning of the second half of the last century. Among the pioneers that have promoted awareness on environmental issues were Rachel Carson (1962) who was the first one to question the legitimacy for man to claim control over nature and at the same time denounced the risks for man and nature to indiscriminate using polluting and lethal chemicals in agriculture, Barnett and Morse (1963) who theorized the first principles of environmental economy, and Victor Papanek (1971) who appealed to a design characterized by inclusion, social justice and sustainability, rejecting all forms of consumerism and laying the foundations for sensitive and responsible design in a world lacking resources and energy.

After these contributions, The Limits of Growth report followed (Meadows et alii, 1972; Meadows, Meadows and Randers, 2004). It highlighted the unsustainability of a growth model based on the reckless use of resources and environmental pollution and the first United Nations Conference on the Human Environment in

Stockholm – when the United Nations Environment Program was established – forerunners that inspired the well-known Our Common Future report (also known as the Brundtland Report) in which the first definition of 'sustainable development' was created: «[…] Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs» (WCED, 1987, p. 15). This definition was quoted multiple times and was integrated with new and specific variations from numerous institutional documents of strategic aim that came in succession up to the present day at an increasingly fast pace, starting with Agenda 21 (UN, 1992). It was a complex Program, (a sort of manual) originating from the Rio Conference which identifies the actions to be taken at a global and local level in each area affected by climatic-environmental and socio-economic emergencies and specifies the means of implementation of the program (scientific, financial and legal, training, information, international cooperation).

At the beginning of the new millennium, new indications were developed, aiming to fill some gaps of the previous guidelines and the European Union took on a leading role with the Climate and Energy 20-20-20 Package (European Commission, 2009). It promoted new initiatives in different sectors to reach ambitious environmental goals aimed at a 'preferable future' scenario. Some of the worth-mentioning documents having had the greatest impact on current government policies are The Future We Want (UN, 2012) with new Sustainable Development Goals and the 2030 Agenda for Sustainable Development (signed in 2015 by 193 UN member states), an Action Program for humanity and the planet with 17 Goals and 169 targets «[…] integrated and indivisible and balance the three dimensions of sustainable development: the economic, social and environmental» (UN – General Assembly, 2015, p. 1). This important document shows that the shift towards sustainability takes place not only through actions on buildings but also through values that place man at the centre of the process. In the same year, the European Union adopted the Action Plan called Closing the Loop, a package of measures aimed at guiding the transition towards a circular economy through competitiveness and growth of a sustainable economy focused on reuse and recycling of materials, seeing waste as a 'resource' (European Commission, 2015).

At the same time, new economic approaches and theories were formed, such as Biomimicry (Benyus, 1997), Cradle to Cradle (McDonough and Braungart, 2002), Economics of Happiness (Kahneman, 2007), Blue Economy (Pauli, 2009), Circular Economy (Ellen MacArthur Foundation, 2010), Sharing Economy (Botsman and Rogers, 2010), Qualitative Growth (Capra and Henderson, 2013) and Serene De-growth (Latouche, 2015; Raworth, 2017), focused on sobriety, on the idea of limits and on the '8 R' (Re-evaluate, Reconceptualize, Restructure, Redistribute, Relocate, Reduce, Reuse, Recycle) as possible responses to the planet's emergencies, but also on the six areas of the ReSOLVE action (REgenerate, Share, Optimise, Loop, Virtualise e Exchange; Ellen MacArthur Foundation 2015a) for companies and Countries aiming to shift towards a circular economy, with the aim of sustainable development and of safeguarding future generations (European Commission, 2018). Therefore, the circular economy is a new model rethinking an economic development completely separated from the use of non-renewable limited resources (Ellen MacArthur Foundation, 2015b), as it was suggested first by Walter R. Stahel (1976) – who outlined the characteristics of a 'loop' economy with greater benefits on work, economic development, resource-saving and waste control – then by Frosch and Gallopoulos (1989) – who promoted a 'biologic ecosystem' where the waste of industrial processes become raw materials for other projects – and finally, by McDonough and Braungart (1998, 2002, 2013): according to them, the design should be based on two looping cycles, a technical and a biological one, where resources are kept for as long as possible with minimal loss of quality and waste.

Concerning the environmental subject, the whole world takes the European Union as a model for its many programs, activities, actions and funds promoted and implemented over the last twenty years. The European Green Deal (European Commission, 2019), presented as 'innovative, transformative and revolutionary' (Ossewaarde and Ossewaarde-Lowtoo, 2020) proposed a 'new growth strategy' to build a 'modern economy, efficient in resource management and competitive'. It envisages not only the reduction of CO_2 emissions but also an increase in living standards and new opportunities for work linked to new production, consumption, social and built organization models, all through specific strategies and funds that promote a 'fair transition' even for the most vulnerable citizens. The first pillars of the European Green Deal are the Renovation Wave (European Commission, 2020a) – aimed at stimulating the renovation of the buildings towards climate neutrality and recovery – the Circular Economy Action Plan (European Commission, 2020b) and the NextGenerationEU, a financial tool that provides about 750 billion euros for the implementation of the ecological and digital transformation of the Member States.

However, up to date, the global efforts were mostly focused on the reduction of CO2 emissions, through greater energy efficiency and the use of energy from renewable sources. Resource efficiency and circular growth were the basis of the development program fostered by the New Climate Economy (NCE, 2018) and the World Resources Institute (WRI, 2020): according to them, the 'growth' can be 'separated' from its negative impacts on the environment. However, when sustainability is the aim, a circular economy with 'closed' recycling circuits is prevalent and ignores the indications of experts and researchers saying that to achieve the ambitious objectives set by Paris it is essential to reduce the quantity/volume of non-renewable natural resources used, but above all of the derived waste (Hickel, 2019; EEB, 2020). The European Environment Agency (EEA, 2021) has recently affirmed that the hoped 'separation' is not happening and might never be implemented, supporting this idea with data showing Europe as one of the first areas in the world for consumption and 'stress' on the environment and where the circular economy fuels a growth strategy aimed at the consumption of resources: in 2019, only 12% of materials were recycled in the European Union, while in the rest of the world circularity is decreasing (Circle Economy, 2021).

In a recent contribution, David Ness (2021, p. 28) underlined how the European Union has recently recognised «[…] that conventional approaches are insufficient to make the major shifts required, [and that a considerable reduction] of environmental pressures and impacts would require fundamental transformations to a different type of economy and society». To resume the 'green pact' the European Commission (2021) has launched the New European Bauhaus with a call for projects4 for the built and natural heritage meant for designers, architects, artisans, engineers, scientists and creatives who have submitted projects capable of describing the three key dimensions of one of the main programs of the next seven years in Europe: sustainability, aesthetics and inclusion. The second stage of the program, which will end by 2023, will create pilot projects. In the last stage, which will end by 2024, the results will be disseminated to the widest possible audience in Europe and around the world.

David Ness (2021, p. 29) wonders if our society is ready to face this stage of ecological transition to «[...] develop and grow in quality (e.g. purpose, solidarity, empathy), rather than in quantity (e.g. material standards of living), in a more equitable way [and if it could help] the 'raison d'être' for the New Bauhaus and its driving ambition». Christian Bason et alii (2020) have a positive opinion on it, interpreting the New European Bauhaus as an innovative medium for a wide range of interconnected objectives. Each one needs to be bold, inspiring in the social, cultural and political areas, to build shared identities by transforming an avant-garde into a 'new wave' of systemic change for the necessary ecological and digital transitions. According to Mario Losasso and Simona Verde (2020), the current policies to fight against the environmental condition of polycrisis of our planet need urgent local actions in the near future, starting from the projects with a Green City Approach (OECD, 2016) to urban and environmental redevelopment and regeneration, added in a global strategy capable, on the one hand, to tackle socio-economic issues without hesitation, and on the other, to work with multiple actions to create positive future scenarios and make the built environment more sustainable (in terms of impact), more resilient and less exposed to environmental risks, transforming a crisis into an opportunity.

If the European Union calls upon the creativity of technicians and scientists and the interdisciplinary nature of knowledge, it is useful to recall that there are already design approaches and methods that allow measuring the sustainability of the work and the well-being of the users with qualitative and quantitative markers. In addition to environmental certifications, Life Cycle Assessment, Extended Life

Cycle Costing, Environmental Product Declaration, etc. one of the reference approaches is Zero Waste: it is based on the growing quantity of waste produced by the dangerous combination of extensive exploitation of natural resources and inefficient use of materials in the end-of-life stage (Pietzsch, Ribeiro and Medeiros, 2017; Baratta, 2021). Over the last twenty years, after launching more ecological products with the Integrated Product Policy (European Commission, 2001) and a more virtuous building process with the Life-Cycle Thinking (European Commission, 2003), the European Commission has adopted a series of provisions useful for promoting the recovery, treatment and reuse of products (European Commission, 2008, 2016); it introduced the Extended Producer Responsibility: the producer is asked to take on the responsibility and management of the life cycle stage when the products become waste. Some 'virtuous' European Countries have implemented regulations5, mechanisms and processes allowing a fair percentage of reuse or recycling of waste (Germany, 56%; Austria, 54%; South Korea, 54%, Wales, 52%; European Environmental Bureau and Eunomia, 2019) while many other Countries are under the threshold of 30% (Portugal, 29%; Greece, 21%; Cyprus, 15%; Romania, 11%; Statista, 2021); however, these percentages are too low to reach the Paris goals. This leads us to believe that it is necessary making a more ambitious strategic approach, the Zero Waste, transforming waste from a problem to a resource, eliminating it from the production process, systematically and in advance, without delegating to the end-of-life stage to solve all the problems.

2. Life Cycle Assessment and Environmental Product Declarations

Standards, Labels, and Tools for Ecological Design

2.1 Designing for Sustainability in the Anthropocene: From Principles to Project Intent

According to the Brundtland Commission's definition, sustainable development is about ensuring «that it meets the needs of the present without compromising the ability of future generations to meet their own needs» (WCED, 1987, p. 15). Initially used to define more equitable dynamics of economic development, the term "sustainability" has quickly become commonplace and has been progressively used to characterize not only the development model but also individual actions or situations where this model is applied and materializes (from sustainable production to sustainable market), including the use of recyclable and biodegradable materials, with the aim of limiting the use of fossil fuels, the consumption of non-renewable resources, and the production of waste. This definition has been repeatedly cited and expanded upon with new and specific nuances by numerous institutional documents of strategic guidance that have followed one another to the present day at an ever-increasing pace, starting with Agenda 21 (UN, 1992), the Climate-Energy Package 20-20-20 (European Commission, 2009), and the Sustainable Development Goals of the 2030 Agenda (UN – General Assembly, 2015), through the Action Plan entitled Closing the Loop (European Commission, 2015), the European Green Deal (European Commission, 2019), the Renovation Wave (European Commission, 2020a), the Circular Economy Action Plan (European Commission, 2020b), and the Next Generation EU (European Commission, 2020c), reaching the New European Bauhaus (European Commission, 2021).

The current geological era has been termed the "Anthropocene", a term with which Paul Crutzen and Eugene Stoermer (2000) emphasize the central role of human activity on the 'grave condition' of the Earth's ecosystem and the fact that such impacts will continue for long periods. Although the authors themselves consider it somewhat arbitrary to assign a date to the beginning of the Anthropocene, they place it in the second half of the 18th century, because it is during the last two centuries that «the global effects of human activities have become clearly noticeable, [and this date] coincides with James Watt's invention of the steam engine in 1784» (Crutzen and Stoermer, 2000, pp. 17-18). The authors argue: «Without major catastrophes like an enormous volcanic eruption, an unexpected epidemic, a large-scale nuclear war, an asteroid impact, a new ice age, or continued plundering of Earth's resources by partially still primitive technology [...] mankind will remain a major geological force for many millennia, maybe millions of years, to come, [so it is necessary] to develop a world-wide accepted strategy leading to sustainability of ecosystems against human induced stresses will be one of the great future tasks of mankind, requiring intensive research efforts and wise application of the knowledge thus acquired» (Crutzen and Stoermer, 2000, p. 18).

However, despite the environmental impact of the entirety of human productive activities (the anthropic footprint on the ecosystem) being recognized long enough to characterize the geological era we are going through – the Anthropocene, indeed – it seems that designers have not really taken responsibility for the increasingly evident problem. Already in 1972 Papanek stated: «There are professions more harmful than industrial design, but only a very few of them» (Papanek, 1972, p. 18). From this point, the international debate on design has developed an increasingly marked sensitivity about the environmental issue until reasserting the ecological centrality of the project in the concept of ecodesign (Borthwick et al., 2022). However, it is appropriate to note that this term is tautological or at least hyperbolic because, as Paolo Tamborrini (2009, p.

7) insists, all design is, in a strict sense, ecological: there is no such thing as non-ecological design just as there cannot be non-ethical or non-functional design. A case in point of the maturity of this debate is the "Broken Nature" exhibition curated by Paola Antonelli at the XXII Triennale di Milano: «*Fino ad oggi gran parte del design è stato uno strumento potente dell'Antropocene [ma] il design dovrebbe essere centrato non solo sull'essere umano, ma sul futuro della biosfera*» (Antonelli, 2019, pp. 19, 38). Thus, there is a progressive shift towards methodological approaches where the absolute centrality of man wanes (Badalucco, 2022), moving from Human-centered Design to Life-centered Design (Borthwick et al., 2022). In this perspective, the latest indication by Donald Norman towards a Humanity-centered Design is to be understood, one that embraces «the entire globe: all living things; the quality of the land, water, and air; the loss of species; the changes in climate» (Norman, 2023, p. 188).

For this purpose, industrial and scientific research over the last two decades has begun to focus its attention on "low-energy" products, their production method, and recycling possibilities: beyond technical and aesthetic characteristics, environmental aspects based on Life Cycle Assessment (LCA) are starting to gain importance already in the initial phase of the decision-making process, thus optimizing the production processes of materials, the consumption of non-renewable resources, and the related impacts on the ecosystem and on humans (Campioli et al., 2018). From a business perspective, the next step is to identify communication tools to guide consumers towards products that pay special attention to environmental sustainability. Among the various tools available, environmental labels stand out for their potential to facilitate producer-consumer communication (Bengtsson, 2018), in providing accurate information about a product's impact on the environment throughout its entire life cycle (Fan et al., 2019), and in guiding consumer behavior towards more informed and environmentally respectful purchasing decisions (Marrucci et al., 2019).

2.2 LCA as a Design Lens: Turning Impacts into Choices (materials, processes, systems)

Process, production/creation and product innovations are fostered by the (European, national and local) legislation – nowadays mostly on the environmental subject – and by market mechanisms that stimulate a productive competition for the professionals on the continuous enhancement of the product compared to a constantly changing demand made by planners, builders, buyers and final users. The difficulty of the subject corresponds to a quite complex framework of environmental directives – somehow still fragmented – requiring quite a massive effort to be implemented and most of all to verify the environmental effectiveness of the strategies enforced over the last few years. A first attempt at a systemic approach can be found in the Europe 2020 Strategy and in particular in A Resource Efficient Europe objective (European Commission, 2011a, 2011b), which provides for the delineation of a set of economic-financial tools to assess the real costs and benefits of the use of resources and to encourage the use, in the long run, of solutions designed to an efficient use of natural resources.

The goal of reaching high performances of the materials concerning for to environmental indicators, despite the complexity of the required framework to which the project must respond, gives to the project a double challenge. The first one is the relationship between the project and the matter: the research started over the last few years on the bio-based materials (Maskell et alii, 2015; Onchiri et alii, 2014) are emblematic of the possibility of designing the characteristics of the materials not only from a technical performance–as for the advent of composite materials – and aesthetic point of view, but also from the environmental performance point of view. The second challenge concerns the opportunity to optimize the production processes of materials to reduce the most expensive stages from the point of view of resource consumption and generated impacts (Campioli et alii, 2018), enhancing 'low energy consumption' solutions. In this context, a useful tool for assessing the environmental impacts of materials is the Environmental Product Declaration (EPD) which aims to contribute to reducing the impact on climate of the building sector by encouraging planners and designers to use the LCA while planning and designing buildings (Bovea et alii, 2014; Pacheco-Torgal, 2014).

2.3 Specifying for Impact: Using EPD and Environmental Labels in Material Selection

The Environmental Product Declaration (EPD) is one of the most recommended methods to report the environmental impacts of building materials. EPD is a certified environmental product declaration that provides environmental data on the life cycle of products in accordance with the international standard ISO 14025 (2006), is «[…] the input for a holistic building assessment considering the functional and technical performances in a building context. For a producer, this also means that his contribution to higher sustainability (environmentally, socially and economically) of course should be done by big and small improvements on every step in the building chain» (Gargari et alii, 2013, p. 107). It is a voluntary project decided by the companies that through this tool can communicate the environmental data of their products. These data are processed by one or more Organizations, based on Life Cycle Assessment (LCA) in accordance with the ISO 14040 (2006) series of standards and are independently verified.

Therefore, the LCA method can provide important information on the stages of the whole life cycle to reduce environmental loads and impacts, also through the use of open access software (OpenLCA, 2019; SimaPro, 2019). This is why many Green Building Rating Systems have added LCA indicators in the criteria relating to materials and have fostered the use of products with EPD certification, allowing to identify the best material during the design stage based on verified environmental information. It should be noted that only one protocol, the German DGNB (2019), was born with the LCA evaluation of the building among the first criteria of the protocol, virtuously activating the whole supply chain and leading to a quick increase of EPD certified products, favouring the elimination of irrelevant and misleading data and enhancing primary data strictly linked to the specific product used in the building, stimulating the production sector to direct competition and environmental innovation of products. The general objective of EPD is to encourage the demand and supply of products entailing less stress on the environment while allowing the comparison between products that have the same function.

The ISO 14020:2000 standard, recently replaced by the ISO 14020:2022 standard, classifies environmental labels into three types: Type I label, which describes the environmental impact of a product or services, is based on voluntary action and is regulated by ISO 14024:1999, replaced by ISO 14024:2018, which is currently undergoing the revision process; Type II label, consisting of self-declared environmental statements by companies and organizations without verification by third parties, is regulated by ISO 14021:1999, replaced by ISO 14021:2016; Type III label or Environmental Product Declaration (EPD), regulated by ISO 14025:2006, provides information, verified by an independent third party, based on compliance with a set of predefined Product Category Rules (PCR) for each product category. This allows for the comparison of relevant environmental characteristics of products within the same category and communicates quantitative information both for producers and distributors (business-to-business) and for the end consumer (business-to-consumer).

The developing process of an EPD consists of four stages: 1) the selection of type II Environmental Declaration Programmes; 2) the research of Product Category Rule (PCR) for the product that must be declared (if there is not a Product Category Rule for the product category, it must be created); 3) the creation of a EPD draft based on the implementation of the LCA method, abide by the rules of the EPD Programme and the outlining of a specific PCR for that product category; 4) the verification process that has to prove, before the EPD publication that the data collection and the enforcement of the LCA method are made according to the PCR and meet all ISO requirements.

The EN 15804:2012+A2:2019+AC:2021 standard specifies the basic rules for EPDs relating to the category of building materials, as a guarantee that all Declarations are uniformly represented and verified. Specifically, the Product Category Rule (PCR) must list the stages of the life cycle to be included, the parameters to comply with and how the parameters must be collected and reported. The life cycle stages are established by the EN 15804:2012+A2:2019+AC:2021: Product stage, Construction stage, Use stage, End of life stage, and an optional module Reuse-recovery (D).

The Environmental Product Declaration (EPD) has to facilitate the comparison between products' environmental characteristics that meet equivalent functional requirements. The information included basically concerns: identification and description of the organization that makes the declaration; the product description; the name of the programme and the address of the programme manager and, if necessary, the logo and website; the identification of the PCR; the publication date and the validity period; Life Cycle Analysis data (LCA); additional environmental information; the presence of materials and substances that must be declared, for example substances that can negatively affect public health and the environment at all stages of its life cycle; information on the stages that have not been taken into consideration, if the declaration is not based on a 'cradle to grave' LCA.

The LCA results are divided into three categories on Environmental Impact, Use of Resources, Output Flows and Waste Categories. The Environmental Impact includes the parameters relating to the global warming potential, stratospheric ozone layer depletion, soil and water acidification potential, eutrophication potential, tropospheric ozone and photochemical oxidants formation potential, abiotic degradation of non-fossil resources potential, abiotic degradation of fossil resources potential. The Use of Resources includes the parameters on the use of: renewable primary energies as an energy source; renewable primary energy resources as raw materials; renewable primary energy resources; non-renewable primary energies as energy sources; non–renewable primary energy resources such as raw materials; non-renewable primary energy resources; secondary materials; secondary renewable fuels; non-renewable secondary fuels; net consumption of water resources. In the Output Flows and Waste Categories, the following parameters are included: hazardous waste disposed of, non-hazardous waste disposed of, radioactive waste disposed of, components destined for re-use, materials destined for recycling, materials destined for energy recovery, exported electricity, and exported thermal energy. Finally, additional information on environmental issues can be provided such as the potential impact on biodiversity or the assessment of risks to public health and the environment.

Among the many independent Organizations or Highly Organized Structures that develop the EPD, it is certainly worth mentioning the International EPD® System which, established in 1999, was the first EPD programme developed on a global scale and still is one of the most widespread in Europe (Hunsager et alii, 2014).

2.4 Adoption, Limits, and Integration into Design Practice

The current regulatory framework (Regulation 305/2011/UE on construction products, ZEB directive, CEN standards, GPP, etc.) and the many operational tools available (environmental assessment protocols, EPD certification, etc.), fostered by different bodies and born in different contexts and with different purposes, although worthy of having started a sustainability programme in building, they often appear in competition/conflict, generating confusion and disorientation among stakeholders. The environmental subject is often dealt with in a fragmentary way through the breakdown into sub-themes that leads to seek the optimization of some aspects to the detriment of others, without a systemic approach. One of the environmental certification tools that the building sector can use to address the environmental issue and to communicate the environmental performance of its materials and components, but also to convey the process and product innovation, as reported in this section, can be supplied by the Environmental Product Declaration, regulated by ISO 14025 (2006).

The need to be more transparent on environmental information is mandatory and can no longer be avoided, and in this regard, the increase of EPDs published over the last few years underlines this aspect. One of the basic characteristics of the EPD is the possibility of comparing the environmental aspects of the evaluated products, as in the examination of the case studies. However, as it is highlighted in this section, this can happen correctly only if the same system boundaries are taken into consideration. Despite the efforts dedicated to the standardization of the declaration rules, especially with the implementation of EN 15804, this aspect must be considered more carefully.

Among the subjects that can benefit from it, we include the producers, who can transparently declare the environmental performance of their products, the designers, who can select material also based on its environmental profile, and the users, whose purchases can be more informed and respectful of the environment. Since it is a voluntary-based tool, understanding the reasons that can push manufacturers to use it is important. According to a study published in 2016 (Ibáñez-Forés et alii, 2016), 80% of producers state that the greatest limitation of the EPD lies in the fact that many users still do not know this tool, while its strength lies in the objectivity of the results reported and in the fact that using this tool improves the image of the company. Therefore, the dissemination of EPDs has not to be taken for granted because, on the one hand – to paraphrase Sinopoli and Tatano (2012) – the tool is taken in slowly before being able to change long-established practices, on the other, it must deal with limited knowledge or reticent professionals.

In Italy, an important boost to the dissemination of EPDs can come from the National Action Plan on Green Public Procurement (NAPGPP) which, the Italian Ministerial Decree of 11 October 2017 took into effect the Minimum Environmental Criteria (CAM) for public works (MATTM, 2017). These Criteria, among other things, establish the percentages of materials built with, even partially, recovered or recycled materials, which can also be declared through a Type III Environmental Product Declaration. Actually, two recent surveys on the implementation of CAMs – in the first (short) reference period – do not show a prompt response from the Public Administration: the first survey reports that in 2017 on a sample of 40 Municipalities having organized 119 tenders linked to building, only 6 (5%) have included CAMs among the project requirements (Point 3 and Associazione dei Comuni Virtuosi, 2019); the second report, led by the Osservatorio Appalti Verdi of Legambiente on a sample of 54 administrative centres, reports a slightly higher percentage, 7.1%

(Nuova Ecologia, 2018). Both data are definitely not satisfactory, but we must take into account that we are in a transition stage in which, despite the Contract Law explicitly refers to the use of CAMs, their implementation clashes with the lack of preparation of the Technical Offices on handling them while evaluating the offers (since there are no official price lists or reference analysis) and with the necessary revision of the economic frameworks of the already planned works.1

'Innovative', 'advanced', 'nanostructured' or 'resilient' are adjectives expressing a change referred to new ways to create and develop materials, components and building systems that today must necessarily be 'eco-friendly', for which the project can be a great driver, provided that its potential is understood and its effectiveness optimized (Lucarelli et alii, 2012). The complexity of the building system, due to the relationships between the different sub-systems and between them and the whole building, requires accurate and detailed planning, capable of optimizing «at the same time technologies [...] that are very different» (Campioli, 2011, p. 64) towards a single purpose: the sustainability of the 'building system'. Maria Chiara Torricelli has the same opinion (2017, p. 24), as she states: «The acceleration in technological innovations from other scientific and industrial areas has shifted the role of technological skills from those who systematize and design technology to those who know how to interpret it, finalize it, use it and make it work in the complex system of the design».

Therefore, EPDs can be an important starting point to develop a new approach towards the project. They can have a significant influence on the evolution of environmental awareness in the building industry, calling design to define technical-building choices with a more sustainable environmental and energy profile, but mostly giving, in every decision-making step, a central role to the environmental impact of the entire life cycle of materials, components and building systems. At the same time, the EPDs can be an excellent lever both for greater and more aware qualifications of designers and companies and for the economy of the sector in increasing the turnover thanks to eco-friendly investments. If this tool was already used in the design stage it would produce a paradigm shift – not immediate and rather complex due to the number of subjects involved and the large amount of information to find and to consider – to change the way of considering materials: from things (products and technologies) to systems (parts linked to each other and to the surrounding environment) conceived throughout their entire life cycle. In addition to the performance, technical and aesthetic characteristics, environmental parameters such as the Embodied Energy and the Embodied Carbon, environmental impacts (for example through EPDs) and the possible effects on public health (for example through the Health Product Declarations) and, obviously, the economic effects (Arroyo et alii, 2012) would support the decision-making stage. Everything would be organized systemically through software that finds valid operational support in the Building Information Modeling (BIM).

3. Digital Tools for Ecological Design

3.1 Designing with Data: Parametric Models and Integrated Workflows

Vladimir Bazjanac, a researcher at Lawrence Berkeley National Laboratory at the University of California, said in the 1990s: «the design and construction process of buildings has quickly changed. The change is especially due to the rising of the BIM method and its intrinsic capability of ensuring the righteousness of the artifact data in every step of its life cycle, allowing an integrated realization of the order that until now h impossible». Although it is one of the driving sectors of our economy, the construction world is perhaps one that historically has shown greater resistance to innovation: innovations are undergoing slow evolution and with the same slowness they are perceived by builders and designers, resulting in not few problems of adaptation: «Innovation, in the building industry, is the result of its interaction with an increasingly advanced industrialization reality. This meeting can have a positive effect only if mediated and regulated by a culturally prepared designer» (Nardi, 2003).

In recent decades, professional figures have changed and design tools have evolved: moving from CAD to 3D digital instruments; these tools have created a profound transformation into contemporary production through a repertoire of infinite forms and contents which can be traced back to what in 2008 Patrik Schumacher defined Parametric Architecture, free from the stereotypes of tradition

3.1 - Aqua Tower (Chicago, 2010) by Studio Gang (credits: studiogang.com/projects/aqua-tower).

3.2, 3.3 - Aqua Tower (Chicago, 2010) by Studio Gang (credits: studiogang.com/projects/aqua-tower).

and the form-function relationship, direct expression of parameters and their dealings, mathematically determined, to the BIM software (Building Information Modelling). The relevant data of the building are stored, combined and digitally linked in it to allow a greater level of integration between its technological components, checking in advance the possible interferences and eliminating design and implementation errors [**Figg. 3.1-3.11**]. The figure of the architect was then enriched with the skills introduced by using new digital manufacturing processes: not only he has to design forms to be realized with sophisticated machinery, but he must acquire programming skills and a profound knowledge on manufacturing techniques and on materials. We are moving towards a production capable of overturning the traditional designer-producer-performer-user relationship: this is the dawn of a new era, when self-producers, also known as Makers, will become the main operators of the building process (Anderson, 2010).

3.2 From Design to Production: Digital Fabrication

It is a process through which it is possible to achieve solid and three-dimensional objects starting from digital designs; it is used in manufacturing for the rapid creation of models and prototypes, but also in the automotive and aerospace industries. It is common opinion that digital manufacturing is ushering in a new era for the building industry (Gershenfeld, 2005; Anderson, 2010). Today, as Neri Oxman, architect and founder of the Mediated Materia group at the MIT Media Lab, points out, «digital technologies, as an additive production, enable artisans and industry to merge, generating crafts with the help of technology». At the pace of current research, it is likely that in the near future buildings will be of the 'hybrid' type, partially built with traditional systems and partially printed in 3D. What surely makes 3D printing interesting for the building sector is the ability to enhance the typical benefits of industrial production (save resources, reduce waste, quality control of the finished product), with almost an unlimited adaptability to the specific needs of the project. So far, serial-produced technologies have had great

3.4, 3.5 - Bosjes Chapel (2011-2016) by Steyn Studio
(credits: www.steynstudio.com/projects/bosjes_chapel).

3.6, 3.7, 3.8 - Harbin Opera House (2010-2015) by MAD Architects (credits: www.i-mad.com/projects/harbin-opera-house).

3.9, 3.10, 3.11 - Harbin Opera House (2010-2015) by MAD Architects (credits: www.i-mad.com/projects/harbin-opera-house).

3.12, 3.13, 3.14, 3.15 - ICD/ITKE Research Pavilion in Stuttgart (2015-2016) by Achim Menges and Jan Knippers (credits: www.itke.uni-stuttgart.de/research/icd-itke-research-pavilions/icd-itke-research-pavilion-2015-16).


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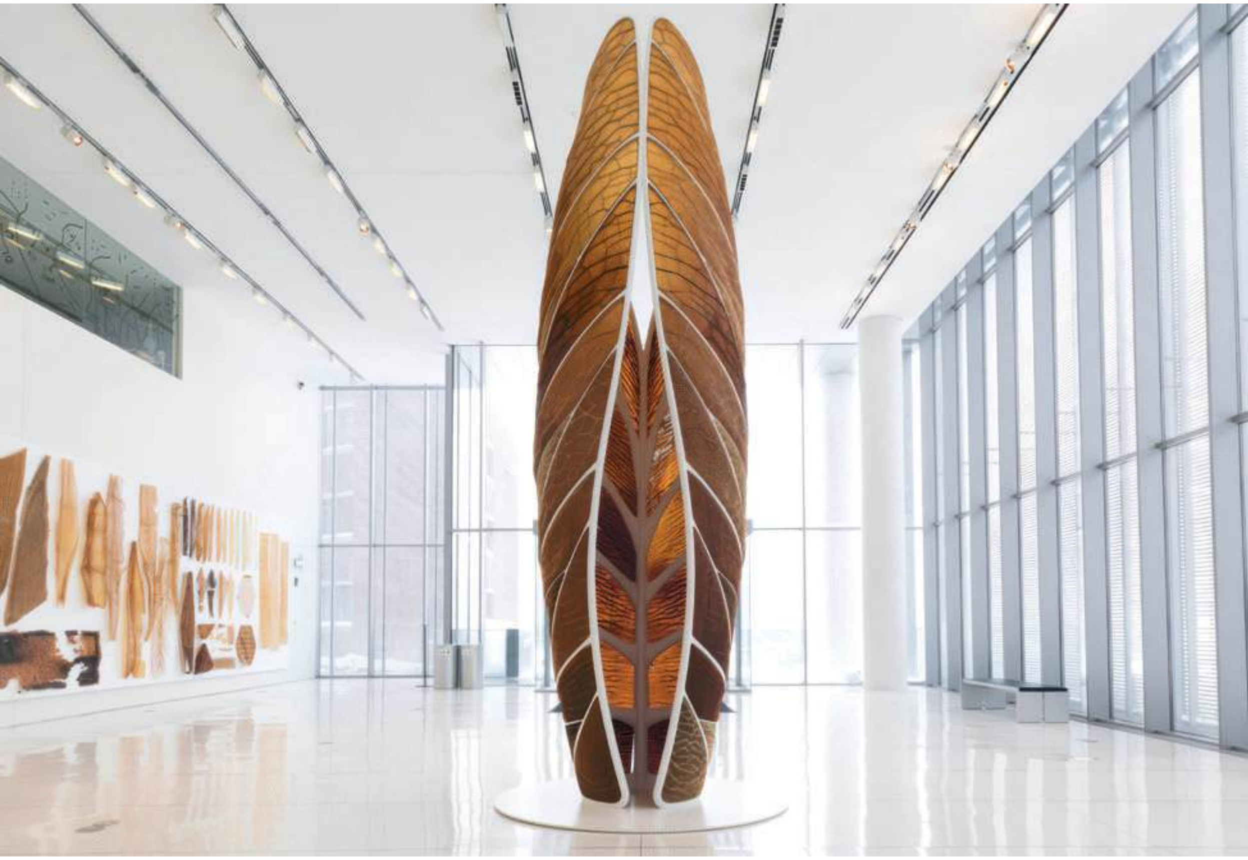
difficulty to gain a foothold, mostly because of the rigidity of the architectural language. But, with 3D printing a diametrically opposed scenario opens up, in which the means of production can fully support the project in its 'formal' and complex geometrical articulations.

The Gehry & Partners LLP Studio experimented with the digital manufacturing process for the first time at the end of 1980 and in 1992 used it to construct the fish-shaped pavilion on the Barcelona Waterfront: production and assembly of the various structural components have been governed exclusively by the digital model, since producers could not operate with traditional tools. The use of modelling software has drastically expanded design possibilities reducing time and possible errors due to information transfer, whereas digital manufacturing technologies have greatly expanded the range of what can be built (Kolarevic, 2003). The combination of these two tools has made it possible to imagine and create a mass architecture that is also highly customized, beyond all limits of complexity and efficiency, creating fertile ground for experimentation on machines, manufacturing techniques and materials used for construction [Figg. 3.12-3.15].

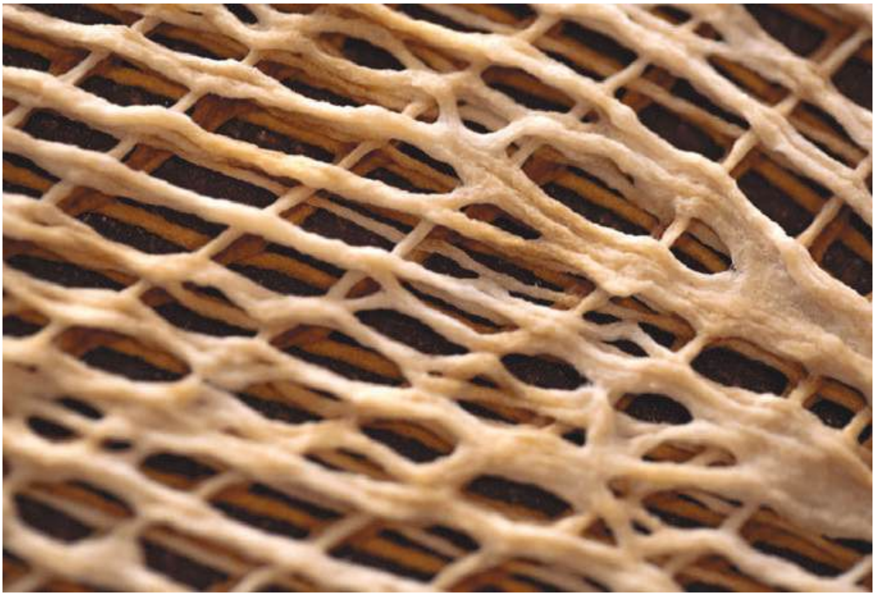
3.3 3D Printing: Processes and Materials

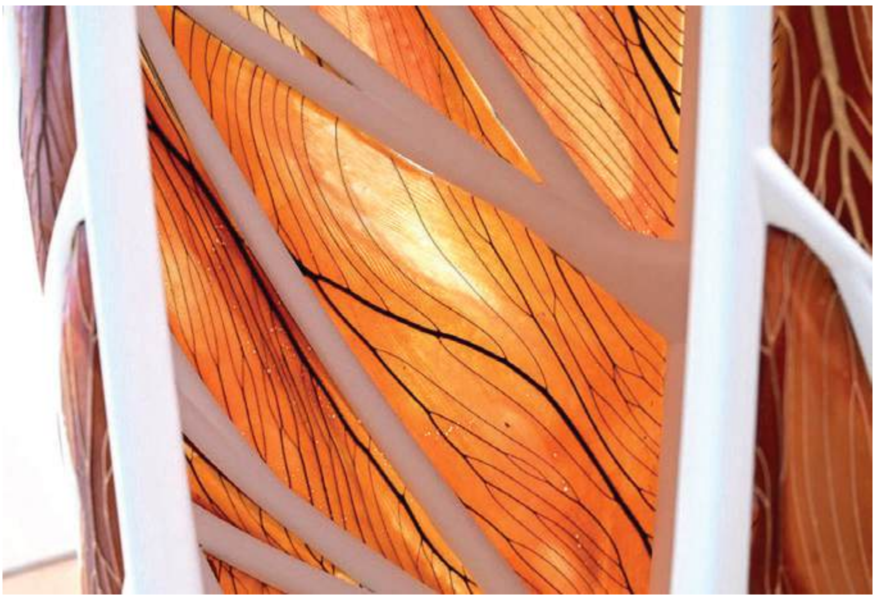
3D printing was born in 1986 with the registration of Chuck Hull's patent on stereolithography, a patent that permits the realization of objects by subsequent solidified resin layers. In practice, an ultraviolet light is concentrated on the surface of a tub filled with liquid photopolymers and, through specific software and hardware, draws every layer of the object onto the liquid surface, which is hardened and polymerized (Hull, 1986). Since its creation, 3D printing has evolved thanks to different technologies, such as: Stereolithography (SLA), Selective Laser Sintering (SLS), Digital Light Processing (DLP), PolyJET, Fused Deposition Modelling (FDM), Laminated Object Manufacturing (LOM), Selective Laser Melting (SLM), Two-Photon Polymerization (2PP), Direct Metal Laser Sintering (DLMS), Selective Heat Sintering (SHS), Anti-Gravity Object Modelling (AOM), the recent Stress Line Additive Manufacturing (SLAM). It has also evolved



3.16 - Aguahoja III, a pavilion robotically manufactured from organic matter (2021) by Neri Oxman (credits: www.dezeen.com/2021/11/19/neri-oxman-aguahoja-iii-pavilion-robotically-fabricated).

3.17, 3.18, 3.19 - Aguahoja III, a pavilion robotically manufactured from organic matter (2021) by Neri Oxman (credits: www.dezeen.com/2021/11/19/neri-oxman-aguahoja-iii-pavilion-robotically-fabricated).





by using different materials, with specific mechanical characteristics, printed alone and in combination, to be used in areas ranging from industry to crafts, from medical to food, making the prototyping of new products accessible to everyone. Some of the most used materials are: ABS (Acrylonitrile Butadiene Styrene) or PLA (Polylactic Acid) made from corn starch or sugar cane, biodegradable and able to increase its range of applications and to give to the printed material a wood, metal and sandstone appearance (ColorFabb, 2016).

Over the last decades, many low-cost 3D printers have been put on the market. The first one, produced by 3D Systems, was Actua 2100 in 1996, that deposited wax in subsequent layers using the ink-jet printing mechanism. Since then, machine tool manufacturers have developed several devices that use both subtractive and additive technologies but that are also equipped with accessories to cut or mill (Zelinski, 2014). Additive manufacturing technology continues to improve in print detail accuracy, in reducing the time required to make an object, while the size of printable objects grows, and materials and equipment are increasingly affordable and more accessible. Today, there are fifty different additive manufacturing processes, based on different chemical working principles, which can be used at any stage in the design and manufacture of a component with modest limitations related to geometry, complexity, or composition of the material.

Construction activity in general, which consists mainly of the laying of different components and the overlapping of subsequent layers of material, can be considered an additive process (Naboni and Paoletti, 2015). Additive production can be applied to the construction industry essentially in two ways: to produce components to be assembled into larger structures, or to 'print' on large-scale whole architectural structures. Since the mid-1990s, several research groups and industries have attempted to apply additive production to the scale of the building, trying to overcome the main limit represented by the size of the machines compared to the scale of the buildings. The increase of automation in the building industry has been and is still rather slow for several reasons including: the traditional design approach is not adaptable to the new process and innovation; the technologies available are inadequate for large-scale realization;

there is still a search on materials with physical and mechanical characteristics compatible with the printing process; and the machines are quite expensive. On the other hand, the building industry still faces a high fatal accidents and injuries rate in building sites, and a low efficiency and a low-quality production. 3D printing, if employed in the building industry, promises to limit the problems related to human errors, to respect deadlines, to enhance designers' creativity on geometries and complex shapes, to improve the functionality of the structures, the control on materials and on the quality of the finishes (Fischer et alii, 2013).

Among the different printing processes, the additive manufacturing stands out. It is a process of incremental formation executed by the addition of subsequent layers of materials without using supplementary instruments or moulds (Kolarevic, 2003). Physical and chemical processes led to the creation of homogeneous solid forms, composed of amorphous materials such as liquids, powders, gases and fibres. This process offers a wide range of flexibility and a great economic potential, since the components are made directly from natural materials and allow to produce unique components, which would not be economically sustainable if produced with traditional manufacturing techniques (Hauschild and Karzel, 2011). This feature, together with the possibility of freely creating complex forms, makes the additive manufacturing process particularly relevant within the perspective of advanced customization, and explains the increasing involvement of architects in the development of techniques and applications in this field.

3.4 Future Design Frontiers: Adaptive Printing and Human-Robot Making

Today, the potential of advanced digital design and manufacturing technologies is not limited to a small number of operators, but it is a global priority for the development of a new industrial paradigm, as demonstrated by the US government recent funding in favour of the research and the development of new technologies and to set up a network of 15 innovative production institutes in 2015. In the building industry, digital manufacturing is now a reality in the production of free-form components for the casing or for the technical elements capable of 'materializing' the technological complexity and the formal specificity of some architectural projects. The transition from component to large scale requires thorough research in different themes.

First, on the materials, on their physical and mechanical properties and on their behaviour when printed. The 3D printing process works by adding material through subsequent layers and makes this technology flexible and usable with polymers, metals, composites (such as ABS with added resin and carbon fibre) and cement materials. However, thanks to the engineering of materials and synthetic biology, we need to deepen the search for more sustainable materials (more resistant, opaque, transparent and insulating) with characteristics that will allow us to create organic digitally-built buildings, in full agreement and respect with nature [Figg. 3.16-3.19]. The research of Neri Oxman on chitin goes in this direction, a biodegradable material based on shrimp shells, with variable density and resistance, that could eventually start to replace plastics, or on some insect wings that are light and strong due to their geometry which concentrates the material along the lines of tension.

At the same time, it is of particular interest the research developed by the MIT Self-Assembly Laboratory, in collaboration with Stratasy Ltd. and Autodesk, on 'printable' nanostructured materials, able to change shape and functionality after their production, thus providing additional features, and applications and performance on command. This new manufacturing process, called '4D printing', may allow to change the properties of printed material (for example, flexibility, porosity, conductivity, optical properties, magnetic properties, etc.) by programming its modifications post-fabrication to fit the shape or the functionality wanted or to decompose it quickly for the benefit of the environment (Campbell et al., 2014). Second, some research is needed on the new software that with 3D printing allows designers and builders to work seamlessly in a digital environment, but often using different applications for modelling the project, for the engineering of shapes, etc. In the rush to better controlling each and every aspect of the workflow (from creation to realization) the risk that software is processed with different languages, without the possibility of exchanging information, requires constant disciplinary research on the interoperability of platforms.

Finally, on the organization of the proceedings, Jeremy Rifkin argues that the marginal cost of man-made labour to produce goods and services will tend to be abandoned with the advancing of intelligent technologies in every sector and in every field of technical and professional applications. What is more realistic is that advanced production technologies will not completely replace traditional ones, which will remain the most appropriate solutions for some applications. It will be necessary to understand how robots and humans can work side by side and study intelligent sensors and man-machine interfaces to start the fourth Industrial Revolution.

4. Timber as an Ecological Material

Evidence, Impacts, and Reuse

4.1 Wood as a Climate Design Resource: Forest Management and Carbon Storage

By defining the biobased economy, the European Commission (2012a) has promoted important challenges, such as the prevention of the natural resource depletion and the reduction of dependency on non-renewable resources; moreover, about climate emergency, most of the Countries that signed the Paris Climate Agreement recognized the need to take urgent action, giving to forests and their products a key role to mitigate CO_2 emissions in the atmosphere (FAO, 2016).

Over the last years, there has been a steady increase in the use of timber as building material in Europe [Figg. 4.1-4.9], China and North America (Food and Agriculture Organization and UNECE, 2018; Howard, McKeever and Liang, 2017). However, while the green building strategies of the European Union do not promote specific materials, many studies and research on green building have underlined the role that forest-based industries and timber buildings can have (Wang, Toppinen and Juslin, 2014), the positive environmental impacts of wood products (Bösch et alii, 2015; González-García et alii, 2011b; Suter, Steubing and Hellweg, 2017), the value of forest ecosystem services, the future potentials and current risks to which they are subject (Ojea et alii, 2016; Ouyang et alii, 2016; Thom and Seidl, 2016). Research and studies are flourishing, especially in the Nordic countries [Fig. 4.10] where timber buildings are considered as one of the most important means to achieve growth based on circular biobased economy (Antikainen et alii, 2017), allowing benefits both in terms of CO_2 emission reduction (Oliver et alii, 2014) and of low-cost creation (Esala, Hietala and Huovari, 2012).

Therefore, forests can play a key role in the transition to low-carbon economies and in the building of a sustainable environment as they represent carbon accumulators and wood products have a lower embodied energy than other products, especially in the building sector that is responsible for 36% of global energy consumption and 39% of CO_2 emissions (UN Environment, 2018). But this role can be crucial only if timber comes from sustainable sources (Lucon et alii, 2014) [Fig. 4.11]. While growing, trees accumulate CO_2 and release oxygen into the environment; while aging, they absorb less and less CO_2, and if they are not cut down, they rot, releasing into the atmosphere the quantity of CO_2 stored during their life cycle. Sustainable forest management provides for cutting only adult plants and replace them with new trees; in wood products made from cut down trees the carbon stays stored, thus representing a carbon dioxide storage tank. At the end of their life cycle, the wood products can be reused for power, for example as biomass. In this case, it is released the same quantity of CO_2 that the tree had previously withdrawn from the atmosphere and the cycle is thus closed in balance, without damaging the environment. Many manufacturers of timber elements have adopted timber biomass thermal power plants that generate power from the waste of woodworking and its recovery at end-of-life. The power produced with this method is used in the production processes, triggering an eco-sustainable energy cycle capable of eliminating carbon emissions, which is not possible with other building materials (especially steel, aluminium and plastic), whose recycling and transformation process demand an enormous quantity of power and an enormous quantity of emissions into the atmosphere.

Measuring Impacts: LCA and EPD

There are many scientific evidences showing how the commonly used building materials (concrete, steel and aluminium) make a crucial contribution, during the production process, to CO_2 emissions into the atmosphere (Akbarnezhad and Xiao, 2017), therefore for a

4.1, 4.2 - Bloomberg Student Center at Johns Hopkins University, Baltimore (2015) by BIG | Bjarke Ingels Group (credits: big.dk).

4.3, 4.4 - Bloomberg Student Center at Johns Hopkins University, Baltimore (2015) by BIG | Bjarke Ingels Group (credits: big.dk).

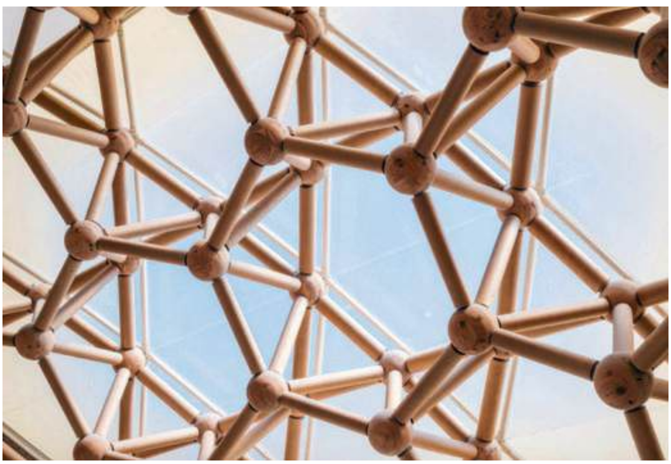
4.5 - Toyota City Museum, Aichi, Japan (2024) by Shigeru Ban Architects (credit: shigerubanarchitects.com/news/toyota-city-museum).

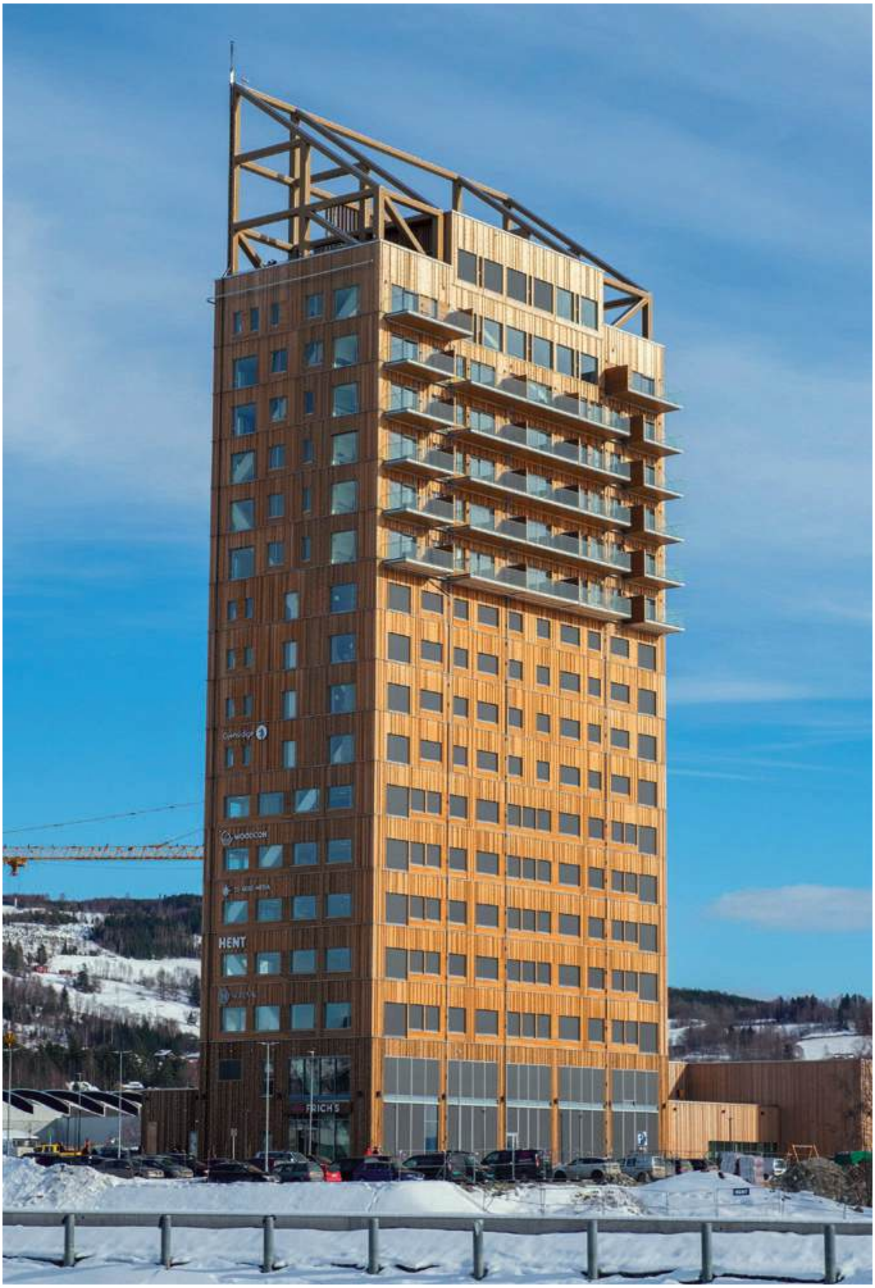
4.6 - Shishi-iwa House No. 2, Japan (2022) by Shigeru Ban Architects (credit: shigerubanarchitects.com/works).

4.7 - Blue Ocean Dome, Osaka, Japan (2022) by Shigeru Ban Architects (credits: shigerubanarchitects.com/news/blue-ocean-pavillion).

4.8 - Blue Ocean Dome, Osaka, Japan (2022) by Shigeru Ban Architects (credits: shigerubanarchitects.com/news/blue-ocean-pavillion).

4.9 - Blue Ocean Dome, Osaka, Japan (2022) by Shigeru Ban Architects (credits: shigerubanarchitects.com/news/blue-ocean-pavillion).





4.10 - The Mjøstårnet in Brumunddal, 2019 (credit: buildingcue.it/mjostarnet-il-grattacielo-inlegno-piu-alto-del-mondo/12256/).

correct analysis of the overall energy balance, the embodied energy take into account the whole life cycle of the material, with an analysis 'cradle-to-grave' that includes the energy needed for the extraction of raw materials, processing and transport, periodic energy for maintenance and final energy for disposal (Hammond and Jones, 2008; Dixit et alii, 2010). An appropriate building materials choice can cause a 17% reduction of the energy used in the construction of a building (Thormark, 2006), and it can reduce the CO_2 emissions by 30% (Gonzalez and Navarro, 2006). In terms of environmental sustainability, it seems fundamental to focus on the use of 'low-energy materials', their production method and recycling possibilities.

A fundamental tool for assessing the environmental impacts of materials is the EPD (Environmental Product Declaration) or Type III Environmental Label.

The production of wood products requires, in general, less energy than the production of most materials, specifically cement and steel (Sathre and González-García, 2014). One of the best known and used databases that gives data on the embodied energy of materials is the Inventory of Carbon and Energy (ICE) created by Hammond and Jones from Bath University (Hammond and Jones, 2019) shows the data on the wood products in the ICE. First, it is important to consider that these data concern only the 'cradle-to-gate' analysis, therefore only the Product stage (A1-A3) is considered. If the data are compared with other materials that are always in the ICE, the embodied carbon of most products is lower than that of materials as Aluminium, Ordinary Portland Cement (OPC) and Steel.

The data including the carbon stored in the timber and those that exclude it; carbon storage can only be requested for timber coming from sustainable sources. This table also shows how carbon storage values are presented as negatives, because, as an example, if 1.5 kg of CO_2 per kilogram of timber is stored and 0.5 kg of CO_2 per kilogram is the carbon embodied to make a timber product (Mod A1-A3) without carbon storage, the embodied carbon with carbon deposit will be -1.0 kg CO_2 per kilogram of timber. The storage of carbon can be applied only to timber transformed in a product and not to the excess timber that will become waste material. Moreover, it is particularly important to consider the end-of-life stage for timber, since the

4.11 - A sustainable forest (credit: thesustainablemag.com/it/ambiente/cosa-impariamo-nella-giornata-internazionale-delle-foreste).

quantity of stored carbon that will reenter the atmosphere depends on the methods used for its end-of-life: incineration, throwing in a landfill, recycling or reuse.

4.2 Designing Timber for a Second Life

Despite the importance of the end-of-life stage, most of the EPDs are limited to the 'cradle to gate' or 'cradle to gate with options' analysis. A study recently published (Scalisi and Sposito, 2019) examines 395 products available on the International EPD System website. The analysis of the 395 EPD files shows that, in most cases, the system limit is 'cradle-to-gate with options', precisely in 46% of the cases; in 29% of the cases the system limit is 'cradle-to-gate' and only in 25% of the cases the system limit is 'cradle to grave'. Furthermore, the research highlights that in the files declaring 'cradle to gate with options' as system limit, besides the mandatory stages A1-A3, most cases show data related only to the A4 stage, among the optional ones, only a small percentage shows data related to A5 stages, among the optional ones, while a few cases show data for stages B1-B7 and C1-C4. The same happens for step D, that is rarely considered.

The end-of-life stage of a building product begins when it is replaced, dismantled and does not have any purpose. Specifically, it includes: C1 (demolition of the building/construction product); C2 (transport of demolition waste including the end-of-life building product in the waste treatment plant); C3 (waste treatment operations for reuse, recovery or recycling); C4 (disposal and linked processes). During the end-of-life step, everything coming out from the system (that is the building) is considered waste until it gets the status of end-of-waste. The end-of-waste status is reached if one of these materials or products meet one of these requirements: it is commonly used for specific purposes; there is a market or a demand for it; it meets technical requirements for specific purposes; its use will not lead to negative effects. The module D refers to the possible reuse/restoration/recycling. About wood products, this section has analysed the EPD files present not only in the International EPD® System but also in the IBU-EPD. Of 91 products analysed, 25 are in the International EPD® System and 66 in the IBU-EPD, 27 of which are of the structural wood product type [Fig. 4.12] and 39 of timber-based panels type [Fig. 4.13]. The analysis confirms the results of the aforementioned research, since the life cycle analysis includes a 'cradle to grave' analysis only in few cases. About the end-of-life stage of wood products, from the 91 files analysed, it is clear that have been taken into account mostly the C3 module (73%) and the D module (77%), while the C1, C2 and C3 have been analysed only in 12%, 29% and 21% of cases respectively. These latter percentages show how, although EPDs give useful information for professionals to choose sustainable materials, they still have limits with respect to the whole analysis of the life cycle (in which all the phases should be taken into account), also in the case of the wood products we have dealt with.

4.3 Designing Timber for Reuse: From Bio-Glues to Adhesive-Free Joints

It is known that wood products coming from sustainably managed forests can have a significantly lower environmental life cycle impact than other common building materials such as cement and steel (Werner and Richter, 2007; Sathre and O'Connor, 2010). But what limits the possibility of recycling them at their end-of-life is mainly the presence of petroleum-based glues such as urea and phenol-formaldehyde. The anisotropic nature of timber and the variability of its properties, which depend on the tree species and climate zones of their origin, have been overcome by composite wood products, made by gluing together smaller pieces, which have created a more homogeneous material with significantly better performances. However, many studies (González-García et alii, 2009) show that the use of petroleum-based glues has a negative impact on the environment, being responsible for polluting emission favouring global warming, the formation of photochemical oxidants and acidification, eutrophication and toxicity phenomena.

The research of the last ten years has, therefore, focused on developing environmentally friendly glues. One of the first studies was carried out by Widsten and Kandelbauer (2008) who evaluated the production of timber fibre panels using a lignin-based glue with enzymes, with good results in the laboratory; Moubarik et alii (2009) proposed the use of resins obtained from corn starch and tannin from the quebracho tree (Schinopsis balansae) used as glue to partially replace the phenol-formaldehyde resin in plywood production, obtaining panels with better mechanical properties and water resistance; González-García et alii (2011a) studied the production of panels using a two-component double sided adhesive made of a timber-based phenolic material and a phenol-oxidizing enzyme. More recent studies are carried out by: Kaufmann, Kolbe and Vallée (2018) on gluten and casein-based glues that have similar performances to epoxy and 2K polyurethane glues, provided that they are used in dry conditions; Nairong et alii (2019) on bio-based glues derived from renewable defatted soy flour and epichlorohydrin, capable of giving to glued Pinus Massoniana plywood a wet shear strength of 0.93 MPa, a parameter in line with the Chinese national legislation. Finally, the experimentation carried out by Guo et alii (2019) on a bio-based polymer composed of a natural monoterpene (β-myrcene) and sulphur dioxide – which can be taken from industrial exhaust gases – whose adhesive properties have been tested on glass, timber, aluminium and copper with promising results.

The methods of connecting timber are also reviewed from a materials science point of view (Bechthold and Weaver, 2017). Friction welding of timber (a process adapted from the metal industry) turns out to be more promising than the use of mechanical fasteners and glues, which limit the reuse of timber in an end-of-life scenario (Hahn et alii, 2014; Stamm, Natterer and Navi, 2005). In the friction welding, an oscillating movement under pressure produces heat at the interface of two timber elements so that pyrolysis occurs between organic materials; maintaining pressure during cooling allows the two layers to bond permanently when the softened material hardens. The technique is particularly interesting for the gluing of several layers of solid timber in the production of CLT panels but the complexity of welding timber in the current production system has prevented its widespread implementation so far. The ongoing project called Towards Adhesive Free Timber Buildings is following this principle. The project is funded by the European Community

4.12 - Above. Structural timber (credit: www.apawood.org/structural-composite-lumber).

4.13 - Under. Timber-based panels (credit: www.borregaard.com/insights/how-to-reduce-manufacturing-costs-in-wood-based-panel).

within the 2014-2020 INTERREG VB North West Europe program and coordinated by the Centre for Materials and Structures of the University of Liverpool. On a long run, the project aims to produce one million cubic metres of wood products without adhesives and 100% recyclable, removing 6,000 tons of toxic adhesives currently used in their production (Keep.eu, 2016).

4.4 Next Timber Design Frontiers

Bioeconomy, circular economy, land use reduction, sustainable use of natural resources, reduction of CO_2 emissions in the atmosphere and recycling are the keywords which the building world must necessarily face in the near future, as the environmental emergency can no longer be postponed [Figg. 4.14, 4.15]. In this light, the use of timber as building material can give an immediate solution to the problem. Timber is a renewable raw material if its production takes place in sustainable forests. Using timber has a twofold benefit for the environment because, when growing, the plants accumulate CO_2 and release oxygen into the environment, a regulated cutting down of adult trees allows to block the stored carbon dioxide which would be dispersed with their death. The possibilities of recycling the material range from the use as biomass for the production of energy (clean, also thanks to the natural and biodegradable adhesives which are being tested and have similar performances to petrol-based and more polluting adhesives) and its reuse, if originally used in dry building systems. It turns out that a closer integration between the forestry, building, energy, industrial and waste management sectors can find in the use of timber as building material an opportunity to significantly reduce the overall impact of the life cycle of a built environment, bringing great energy, environmental and economic benefits (Lucon et alii, 2014; Truong and Gustavsson, 2013).

Over the last two decades, the industrial research and the research promoted by the academic world have made an important contribution through the engineering of this natural material which has become more performing at combined compressive and bending loads, with greater durability and safety (to earthquakes and fires).

Moreover, the study of new static configurations of the building system has favoured the achievement of greater quotas, challenging year by year the consolidated supremacy of similar skyscrapers in steel and reinforced concrete. The phenomenon of the verticalization of cities, which is scarcely present in Europe, except as a very unique situation, is still mainly linked to the desire to create a landmark or a symbolic element, a manifest of a specific company, technology or innovation but it can certainly favour, with its sustainable and smart skyscrapers, the return to a compact, high-density city, favouring better urban comfort and lower land use.

Technical-technological and planning aspects, but also functional, formal and aesthetic issues to be solved through flexibility in the organization of spaces and versatility in establishing intended uses, experimentation with new linguistic forms that in the case of timber will find expressive strength and formal identity through the attention to building details. In this framework, Building Technology can give its contribution through the organization of processes and the implementation of programs, strategies and projects aiming to favour the development of new and more current policies of territorial transformation into different realities for scale and context, investigating functional, social and morphological aspects, setting indicators, criteria and assessment methods for the urban and building project, experimenting type-technological solutions in synergy with industrial production and finally tracing those lines of innovation that will soon allow to build, only with timber, a skyscraper capable of going way beyond the 115 metres of Hyperion, the world's tallest coast redwood.

4.14, 4.15 - Hugo França's wood recreational equipment in Ibirapuera Park (credits: C. Malaguti, 2019).

5. PCM Phase Change Materials for Ecological Design

5.1 Why PCMs in Design: Turning Heat into a Usable Resource

Among the different materials developed with the research at ‘micro’ and ‘nano’ scale, the Phase Change Materials (PCMs) can be a possible solution to reduce the energy demand in the building sector by reducing heating and cooling demand of buildings (Parameshwaran, Harikrishnan and Kalaiselvam, 2010). The Thermal Energy Storage (TES) systems allow to ‘store’ a certain amount of energy in the accumulation stage to be used at a later time (Arce et alii, 2011), and among the different methods used for the heat energy storage, the Latent Heat Thermal Energy Storage (LHTES) uses the characteristics of phase change materials. The PCMs are materials capable of changing their status from solid to liquid and vice versa, depending on the amount of heat they absorb which becomes ‘latent heat’ during warm weather and ‘released heat’ during cold weather (Soares et alii, 2013). These materials are in a solid state at room temperature, but when it rises, they become liquid and accumulate energy in a latent form. The cycle is inverted when the temperature decreases again, they return to the initial temperature. In this case, the PCMs return to a solid state and in this phase change they release the previously stored energy as heat in the environment. Their thermal storage ability is higher than the one of a traditional material having with a certain mass. Thermoregulating materials represent an innovative technological solution in building design, as they give the possibility to reduce the daily fluctuations of the room temperatures through the reduction of indoor temperature peaks, and therefore of the energy consumption necessary for air conditioning the rooms. Furthermore, as a not negligible advantage, it must be noted that they are functional and operational without any type of external power source, and give dynamism and adaptation flexibility to external weather conditions.

One of the first PCMs used in passive solar systems is water. The Water Drum Wall – tested for the first time at the end of the 1940s by Hoyt Hottel and Massachusetts Institute of Technology of Boston's students – works in a rather simple way: the rays of the sun crossing the glass surface are intercepted by a mass of water or another liquid that converts them into heat, distributed by convection or radiation from a ventilated cavity to the served room, through the wall's internal face. The relation between the heat exchange surface and the indoor environment and the accumulation mass also determines the extent of the thermal transfer and its delay. Convective heat transfer through the liquid mass is faster than by conduction within a wall. Therefore, unlike what happens in the Trombe Wall, the heat transfer to the indoor environment by radiation and convection from the inner face of the wall is almost instant (Simmons, 2011). In order to control convective motions, controls delaying heat transfer are necessary: on the inside of the water wall it is necessary to provide an insulating screen with openings at its top and base, while on the opposite side a mobile insulating screen that prevents overheating or, if necessary, outward heat loss (Emmitt, 2012). Starting from Hoyt Hottel pioneering initiative, through the years, other scholars have made an important contribution to the research and experimentation of Water Drum Wall (Briga-Sáa et alii, 2014; Zhongting et alii, 2017), entailing the thought that in the near future we might use water as real building material. «Build with water will represent a new frontier for sustainable architecture, provided that it is based on a new energy model, able to enhance the thermal mass and energy medium of the natural green fluid characteristics. The new architecture must be conceived as a living organism independent from the energy distribution networks, as a trans-structure, energetically self-sufficient, made of multitasking materials, capable of real-time responses for preserving the indoor comfort» (Sposito, 2017, p. 124).

5.2 Selecting PCMs: Matching Temperature Range, Performance, and Use Context

Many studies have been, and still are, carried out on the use of PCMs in buildings to store heat energy, demonstrating the considerable interest for these materials allover the world (Kalnæs and Jelle, 2015; Cabeza et alii, 2011; Baetens, Jelle and Gustavsen, 2010). However, to use the PCMs we should verify a series of thermo-physical, kinetic and chemical requirements, those that have the greatest impact on their effectiveness, among others, are: High latent heat of fusion, High specific heat, High thermal conductivity of solid and liquid phase and liquid phases, little or no sub-cooling during freezing, non-toxic, low price and effective availability (Navarro et alii, 2018; Konstantinidou, 2010) [**Tab. 5.1**].

Thermo-physical Requirements	Kinetic Requirements	Chemical Requirements	Economical & Environmental Requirements
Appropriate melting temperature in the required operating temperature range	High nucleation rate in order to avoid super cooling of the liquid phase	Long term chemical stability of the PCM	Low price and effective availability
High latent heat of fusion	High rate of crystallization to satisfy demands of heat recovery from the storage system	No degradation after freeze/melt cycles	Non-polluting
High specific heat		Complete reversible freeze/melt cycle	Low environmental impact
High thermal conductivity of solid and liquid phases		No corrosiveness	Good recyclability
High density		Non-flammable, non-toxic, non-explosive materials for safety	Low embodied energy
Congruent melting of the PCM			Facility of separation from other materials
Cycling stability			
Small vapor pressure			
Small volume changes			
Little or no sub-cooling during freezing			
No segregation			

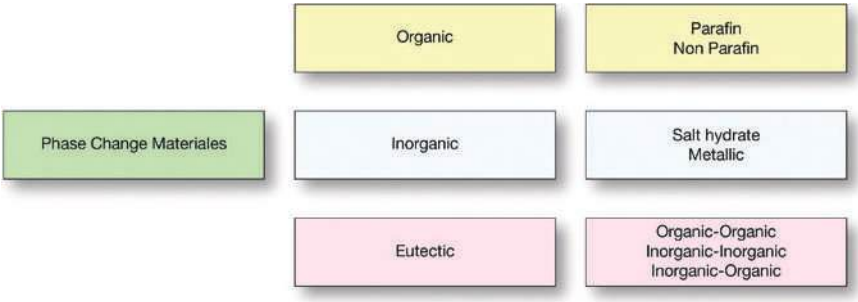
Tab. 5.1 - Thermo-physical, kinetic, chemical, economic and environmental requirements of PCM (source: Konstantinidou, 2010).

The various types of PCMs known to us do not have all the caracteristics listed in Table 5.1. The PCMs are categorized in organic, inorganic and eutectic: paraffin and non-paraffin are: organic PCMs; salt hydrates and metallics are inorganic PCMs; eutectic PCMs are divided into organic-organic, inorganic-inorganic and inorganic-organic **[Tab. 5.2]**.

The PCMs – whether organic, inorganic or eutectic – have some lacks of performances, as stated in Tables 5.3 and 5.4 (Parameshwaran and Kalaiselvam, 2016). As it can be deduced from the Tables 5.3 and 5.4, the organic PCMs are available in a wide range of temperatures, are chemically stable, non-corrosive and nontoxic, do not undergo supercooling or segregation and have a high latent heat of fusion; at the same time they have a low thermal conductivity that could be improved by using a thin encapsulation. Inorganic materials have a good thermal conductivity and a high latent heat of fusion, and are not expensive and non-flammable, but for example salt hydrates have some limitations such as supercooling, segregation and corrosion. On the other hand, metal PCMs do not have a suitable temperature range to be used in the building sector.

Among the most significant criteria for the selection of PCMs there is the melting temperature, whose value has to be compared with the climate zone where the materials will be used in the buildings. Several studies agree that high melting temperatures of PCMs seem more effective for warmer climates, while low melting temperatures can be more efficient for colder climates. Specifically, for the Mediterranean climate the best melting temperature range in winter goes from 18 °C to 22 °C, while in summer it goes from 25 °C to 30 °C (Xiao, Wang and Zhang, 2009; Cabeza et alii, 2011). Paraffin is the most used PCM for indoor cooling, even if in some cases salt hydrates and fatty acid were used. In the future, it would be advantageous to use within the same material and/or components, PCMs with different melting temperatures, to improve the energy performance both in warm and cold seasons (Souayfane, Fardoun and Biwole, 2016).

Given the above-mentioned limits, many studies to ameliorate the mechanism of latent heat energy storage of PCMs have been carried out. They focus on the integration methods of PMCs in building materials such as plaster, plasterboard, cement, insulation and glass



Tab. 5.2 - PCM classification (source: Memon, 2014).

Organic (paraffins and non-paraffins)	Inorganic Salt hydrates	Eutectics
They are available in a range of temperature	They possess high volumetric latent heat storage capacity	They exhibit application-specific sharp phase change temperature (melting temperature)
Values of latent heat of enthalpy are high (e.g., acids have much higher heat of fusion than the paraffins)	They possess low vapor pressure in the melt state	Exhibit slightly high volumetric thermal storage density than the organic compounds
Supercooling degree or superfusion effect is normally low during freezing process	They are non-corrosive, non-reactive, non-flammable, and not dangerous	They possess low or no segregation. Thermal reliability is good with congruent phase transition characteristics
Relatively low segregation even after several thermal cycles (thermal reliability). High thermal stability, congruent phase transition process	Have good compatibility with the conventional construction materials. Recyclable, cost-effective, and ease of availability	
Show self-nucleation and growth rate properties	Exhibit high latent heat of enthalpy and sharper phase transformation. High thermal conductivity with lower volumetric changes during phase change. Safe to the environment in terms of handling and disposing when compared to the paraffins	

Tab. 5.3 - Merits of the LTES materials (source: Parameshwaran and Kalaiselvam, 2016).

Organic (paraffins and non-paraffins)	Inorganic Salt hydrates	Eutectics
Density, thermal conductivity, and latent heat of fusion are inherently lower	Relatively high supercooling properties	Analysis of eutectics for thermal energy storage applications is limited due to the insufficient and non-availability of the thermophysical property data
Inflammable, less compatible with plastic containments	Low degree of nucleation (requires nucleating additives and thickening constituent materials)	In some cases, fatty acid eutectics evolve pungent odor, making them less suitable for PCM wallboard thermal energy storage applications in indoor environments
Larger volumetric changes are possible during charging and discharging (applicable to some grade of organic compounds); expensive by nature	Incongruent phase change and dehydration occur during freezing and melting cycles	
	Decomposition associated with phase separation. Compatibility with some building materials is limited. Exhibit corrosion properties when subjected to most metals. Slightly toxic in nature	

Tab. 5.4 -Limitations of LTES materials (source: Parameshwaran and Kalaiselvam 2016).

(Ascione et alii, 2014; Goia, Perino and Serra, 2013) and the use of nanotechnologies (Jamekhorshid et alii, 2014; Parameshwaran and Kalaiselvam, 2016).

5.3 Designing PCM Composites: Encapsulation, Stability, and Material Integration

PCM incorporation methods are mainly divided into two categories: direct and indirect methods. The direct methods of incorporation, both the wet mixing and immersion (Soares et alii, 2013), were mainly used in the past and have been abandoned due to the possible loss of PCMs and the direct interaction between PCMs and building material which can cause the deterioration of the mechanical and physical characteristics of the materials (Cabeza et alii, 2007). To avoid loss and incompatibility problems caused by the direct contact between building materials and PCMs, most of the studies carried out in recent years have focused on indirect methods, that involve PCMs encapsulation. The encapsulation methods are mainly of three types, based on the size of the capsules: macro-encapsulation, micro-encapsulation and nano-encapsulation. These sizes influence the stability of the PCM, since the smaller the capsule size is, the more durable a product is (Liu et alii, 2015).

The macro-encapsulation method consists of integrating the PCM in containers such as tubes, bags, spheres, porous materials or panels which are generally bigger than 1 cm (Cabeza et alii, 2011). Some of the containers developed as PCMs capsules are steel spheres (Cui et alii, 2017) or porous structures of light-weight aggregates – LWA (Cui, Memon and Liu, 2015; Niall et alii, 2017; Ma and Bai, 2018) to them is usually applied a highly conductive protective coating material to avoid leaks and at the same time increase the speed of heat transfer. Microencapsulated PCM refers to PCM particles enclosed in a thin solid shell (microcapsule) which is usually made of natural and synthetic polymers ranging from 1 μm to 1,000 μm (Navarro et alii, 2016) which prevents the leakage of the phase change material during the solid to liquid phase. Besides preventing PCM leakages during phase change, microencapsulation provides a quick heat transfer through its great surface area per unit of volume (Memon, 2014; Zubair, Hafiz and Shahab, 2018), improving chemical stability and thermic reliability, since the phase separation within the material, during the phase transition, is limited to microscopic distances (Navarro et alii, 2016).

Microencapsulated PCM can also be integrated in concrete. Most of the studies that have integrated microencapsulated PCM in concrete have used the replacement method – replace a specific quantity of fine aggregates with PCMs in the concrete mixtures (Jayalath et alii, 2016; Cao et alii, 2017), since they have a lower loss in resistance compared to mixtures in which PCM is used as an additive (Meshgin, Xi, 2012). Integrate PCM in concrete (Bentz and Turpin, 2007; Jayalath et alii, 2016; D'Alessandro et alii, 2018; Berardi and Gallardo, 2019), especially organic paraffin (Rao, Parameshwaran and Ram, 2018), can increase its heat storage ability, although PCMs can have some negative impacts on physical and mechanical properties of concrete, which depend from the PCM integration method used during the creation of the composite PCM-concrete (Cao et alii, 2017).

Researchers currently tend to reduce the size of the encapsulation to the nanoscale, to maximize the effects of its size and the surface area involved in the heat transfer (Khadiran et alii, 2016). Nanotechnology is the understanding and control of matter at dimensions between approximately 1 and 100 nanometres (a nanometre is equal to one billionth of a metre), where unique phenomena enable novel applications (National Nanotechnology Initiative Strategic Plan, 2011). On this level, fundamental properties such as force, surface/mass relation, conductibility and elasticity can be improved to create materials that can provide a better performance than present materials. In the architectural field, the advent of nanostructured materials concerns the entire building, from the basic structure to the wall-coatings, from lighting to energy production, and most important of all, it is considered crucial for energy efficiency in buildings.

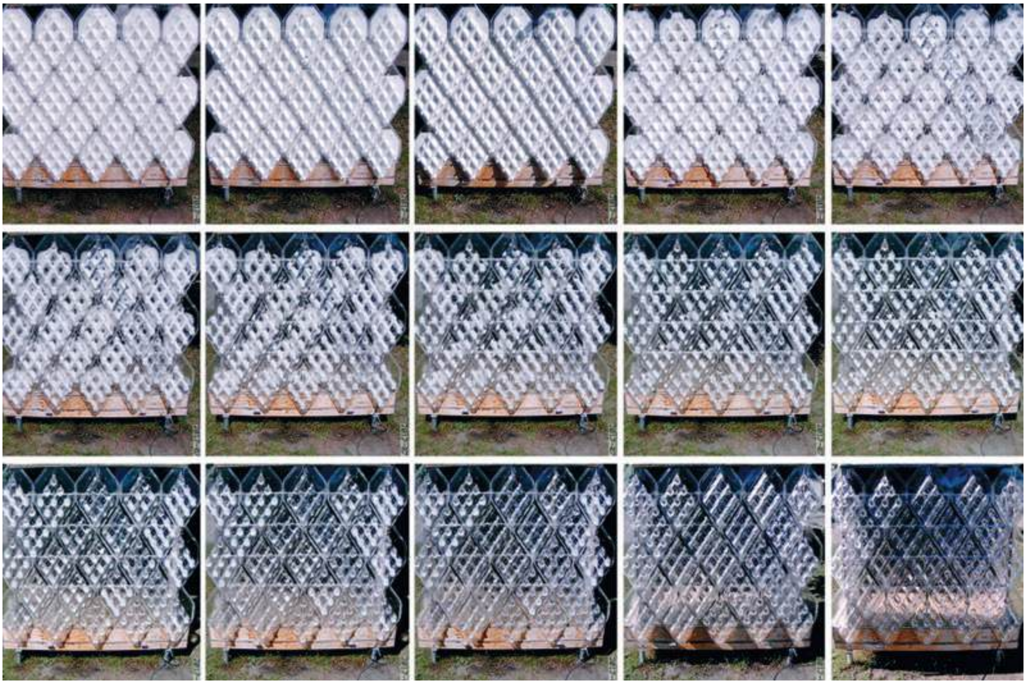
The nano-enhancement of PCMs can be achieved with their encapsulation inside a nano-shell (Sari, Alkan and Bilgin, 2014) or a nano fibre (Moghaddam, Mortazavi and Khaymian, 2015): there are several experimentations that have used PCM nano capsules to improve the thermal properties of cellulose nano fibres (Alzoubi, Albiss and Abu sini, 2020) or PCM nano-encapsulated in a silica shell (De Matteis et alii, 2019), highlighting how the use of nanomaterials can help overcome some limits of PCMs, such as low thermal conductivity (Fang et alii, 2013; Ma, Lin and Sohel, 2016). Other researches concerned the improvement of paraffin thermal conductivity through the dispersion of titanium dioxide nanoparticles (Sami and Nasrin, 2017) but also the development of new phase change materials enhanced with carbon nanotubes (C-PCM) and with a polymer-organic hybrid shell which reduce internal temperature variations and absorb more heat (Cheng et alii, 2020).

5.4 Design Applications and Next Steps: From Prototypes to Scalable Solutions

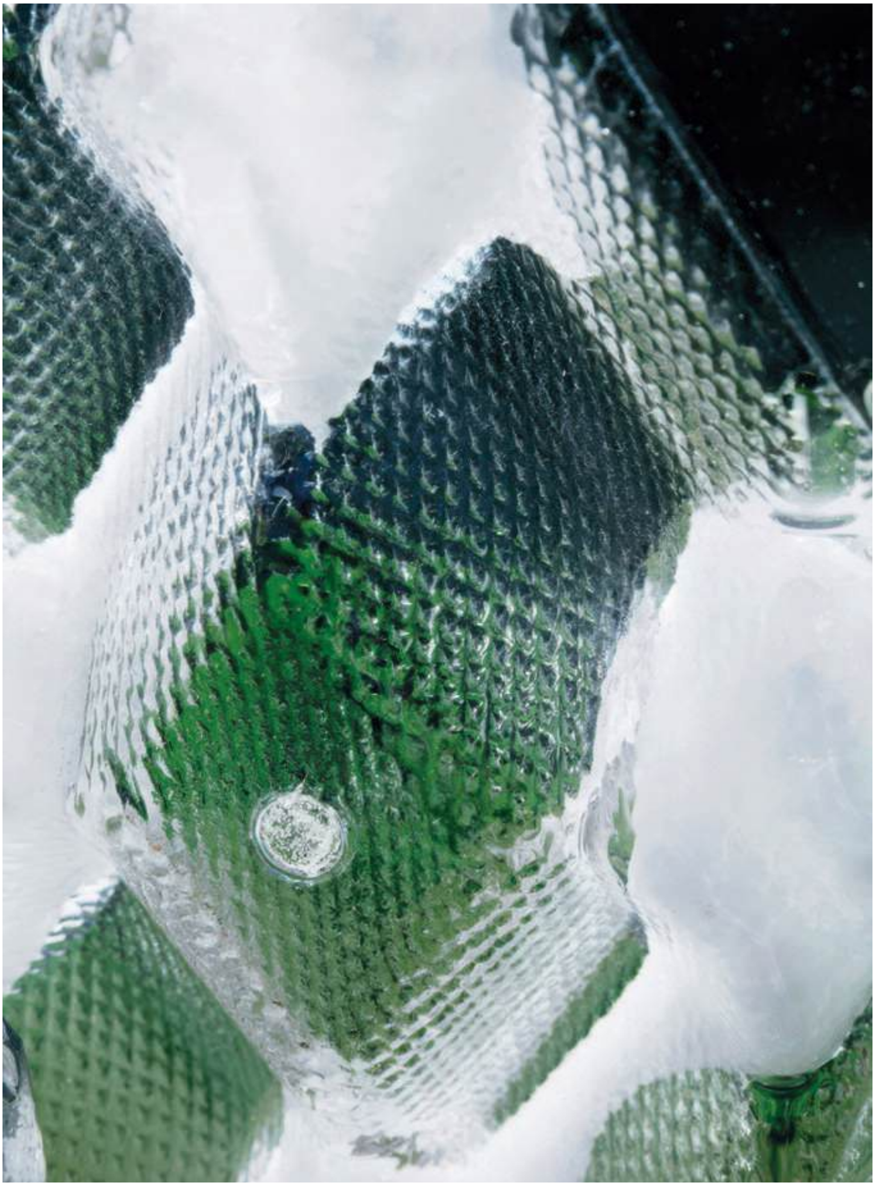
In the near future, the building industry will have to make a meaningful contribution to the protection of ecosystems vulnerable to collapse and the reconstruction of those that have already been affected, also through a significant reduction in the energy required for building operations [Figg. 5.1 - 5.4]. ‘Passive’ systems can play, in this sense, a strategic role, especially if the research will give value to bioengineering and naturalistic engineering methods and techniques tending towards practices designed «[...] to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits» (Cohen-Shacham et alii, 2016, p. 5). This change of perspective will lead the way for a new paradigm that will overturn current approaches: the aim of the projects will no longer be to control natural phenomena to subject them to contingent short-term needs but to support the (unpredictable) dynamics of natural systems, ensuring the operating conditions of systems, subsystems, components and building materials in the long term.

In this sense, Ernesto Antonini (2019) observes that the new paradigm given by biomimetic adaptive envelopes will generate two relevant consequences. The first will be to replace the ‘economic benefits’ objective for those who fund and build a single building

5.1, 5.2 - Phase Change Material (PCM) Facade, Royal Danish Academy (credits: royaldanishacademy.com/en/case/phase-change-material-pcm-facade).



5.3, 5.4 -Phase Change Material (PCM) Facade, Royal Danish Academy (credits: royaldanishacademy.com/en/case/phase-change-material-pcm-facade).



with a long-term vision that will concern 'collective benefits' mostly for future generations, strengthening the idea that if the planet is a 'common good' it needs a development model capable of fixing the catastrophic effects caused by the indiscriminate use of non-renewable resources and the emission of CO_2 into the atmosphere (Tirole, 2017). The second will concern the methods of analysis of natural phenomena: action strategies and intervention planning will have to be systemic and multiscalar, employing shared operational and metric techniques to assess credible cost/benefit balances with the tools provided by Environmental Product Declarations (EPD) methods, of the Life Cycle Assessment (LCA) and their extension to investigate the social aspects (s-LCA) that come into play (Sala et alii, 2015). A vision that analyses the physical area at different scales (resources, materials, buildings, cities, ecosystems and planet) and the social sphere (psychophysical well-being, work, production, consumption, mobility, etc.) and that is aware of the interconnectedness between global and local level is the unprecedented element of this innovative approach that can be implemented immediately thanks to pioneering good practices, as the RELi – REsilience action List by Perkins+Will (Eskew+Dumez+Ripple, 2014) or the REDi – Resilience-based Earthquake Design Initiative for the Next Generation of Buildings by ARUP (2013). Even if they use different methods and standards for assessing resilience, can both be integrated with the most common Sustainable Building Rating Systems.

The great number of published scientific papers and experimental research carried out in the last decade show that the change is occurring and that the future trends in technologies for adaptive facades can be divided into three main categories:

1. Smart Building Operating Systems (SBOS) – an increasing number of components and building elements are managed through the BOS: a software platform for smart facades that implements the use of the IoT and digital applications in buildings by providing services and connectivity to SMACIT technologies – social, mobile, analytics, cloud, smart grid and IoT – to boost user interaction (Dery, Sebastian and van der Meulen, 2017);
2. Service-driven solutions – the risks and uncertainties linked with the functioning of adaptive facades are pushing the users

to outsource performance optimization, monitoring and maintenance services directly to suppliers and manufacturers, because they know the design and engineering of facades in depth (Azcarate-Aguerre, Den Heijer and Klein, 2017);
3. Circularity and materials – European Union law making on circular economy, fosters the industry to produce efficient adaptive facades but using materials providing an environmental gain during their life cycle and that are recyclable within closed and 'regenerative' economic cycles (Ellen MacArthur Foundation, 2013).

Currently the nZEB and ZEB represent less than 5% of new buildings. This percentage is higher in some Countries, such as France, that has very restrictive energy regulations. In the 'rapid transition' scenario for a sustainable future promoted by the International Energy Agency high-performance and near-zero-energy buildings will be more than half of new buildings in 2030, more in advanced economies. If, in the next decade, every country implements specific energy standards for each geographical area, nation, region and climatic zone, especially by enhancing passive adaptive systems and innovative materials for insulation to limit heat loss in cold climates and reduce solar gain in hot climates.

To this purpose, it is essential to organize a strategic plan to lead the building industry in a (quick and aimed) transition stage towards clean energy, low energy consumption and reduced CO_2 emissions and based on three key pillars (IEA, 2019c): Sufficiency – reducing the energy demand and limit expensive unnecessary technological/plant investments through adequate and careful planning and design of buildings without reducing (on the contrary, improving) the well-being standards for users; Efficiency – improve the energy performance of building materials, components and technologies through market policies and actions encouraging the transition to efficient and innovative solutions; Decarbonisation – development, promotion and immediate marketing of already tested technologies that allow to enhance renewable energy sources. The implementation (that is reaching the goals) of this strategic plan is technically possible if the best performing products already available on the market are used since the beginning, through specific 'mandatory performance targets' and 'incentives' useful to cut the high costs of these new materials.

The research on PCMs – which can play an important role in controlling energy consumption for heating and cooling in indoor environments – certainly refers to these three pillars. Taking into account the experimentation and afore-mentioned research, PCMs can take the role of new 'thermoregulatory' paradigm for architecture. To do so, it will be necessary to invest more in research, reasonably assuming that the return on the investment will not only be economic (management costs are significantly lower than mechanized adaptive systems) but also social and environmental and examine in depth a number of issues on various subjects. About environmental issues, it will be necessary to define a new 'adaptive' energy model, based on the physical and thermo-hygrometric characteristics of PCMs, tending, due to their high capacity to absorb latent heat, on the one hand, to the almost energy self-sufficiency in relation to the heating and cooling needs of a building, on the other, to the transfer of surplus heat energy to neighbouring more energy-intensive public buildings, through a system of heat storage and networks.

Conversely, regarding the technological issues, some research areas can concern the creation and development of new PCMs for specific geographic and climatic contexts and building elements and components in which integrate them. It would be important to focus on materials having PCMs with different melting temperatures, to improve the performance of buildings both in warm and cold seasons (Souayfane, Fardoun and Biwole, 2016). Regarding the environmental issue, it should not be overlooked that these innovative storage materials/systems should be analysed especially by taking into account their whole life cycle. Currently, there are only few LCA studies and researches available, limited to paraffin which has significant GWP and PENRT impacts, and to salt hydrates that have a minor impact (Kylili and Fokaides, 2016; Horn et alii, 2018; Nienborg et alii, 2018; Di Bari et alii, 2020).

For the elements and components integrating the PCMs it will be necessary to research on 'multifunctionality' requirements, minimizing the number of technical, durability and endurance elements, while evaluating the overall performance of the system according to an adaptive response to variable (and not always predictable) mechanical and thermal stresses. Moreover, since the new multifunctional components will characterize future architectures with their own shape, size and section, it will be necessary to deepen studies on manufacturing systems – for example digital manufacturing – allowing, according to the individual needs of designers, the personalization of the components and an adequate integration with PCMs, and also a linguistic and formal variety, suited to the intervention background.

In conclusion, to use PCMs as 'thermoregulatory' materials to be integrated into 'adaptive facades' there is definitely a long road ahead but, with thanks to the above-mentioned experimentation and research, it seems set. On the one hand, it seems that, thanks to the use of nanotechnologies, the limit of these materials can be found in the visionary skills of researchers, and on the other, we still must understand how much and when these technologies and materials will be widespread enough to allow a significant reduction of the energy necessary for heating and cooling buildings.

6. Raw Earth

Eco-Material and Nano-Innovation for Design

6.1 Why Raw Earth in Design: Metrics & Selection Criteria

Among the natural materials that can certainly be used in the building industry, providing a valid contribution to the environmental sustainability of buildings, there is rammed earth: an ecological and economic alternative to materials and production processes that are much more energy-intensive. Mud bricks do not require a large amount of energy since, unlike common bricks, they do not need cooking, when considerable quantity of CO_2 is emitted. Conversely, this material does not have a high mechanical strength and can't be used indiscriminately. However, in recent years, rammed earth has received great attention from the scientific community, as shown by the increase of published research, of which over a hundred in Scopus magazines (Pacheco-Torgal and Jalali, 2012). It is true that this quantity is only a small part compared to the articles published on Portland cement, but it has increased at least ten times compared to the articles on rammed earth published in the 1990s.

Several scholars have carried out research that compares the carbon dioxide emissions of buildings made with rammed earth with buildings made with traditional masonry, concluding that the embodied energy used in rammed earth buildings is considerably lower than that energy for traditional masonry buildings, as well as their CO_2 emissions are significantly lower (Morton et alii, 2005; Shukla et alii 2008). The data provided by the Inventory of Carbon and

Energy (Hammond and Jones, 2011) – a database on building materials showing data on embodied energy (MJ/kg) and CO_2 ($kgCO_2/kg$) emissions – shows that the soil has values of 0.45 MJ/kg and 0.023 $kgCO_2/kg$ significantly lower than both Portland cement (5.50 MJ/kg and 0.93 $kgCO_2/kg$) and lime (5.3 MJ/kg and 0,76 $kgCO_2/kg$). These values increase when compressed earth is stabilized with 5% (0.68 MJ/kg and 0.060 $kgCO_2/kg$) or 8% (0.83 MJ/kg and 0.082 $kgCO_2/kg$) cement.

6.2 Design Languages and Performance: From Heritage to Contemporary Practice

Soil is a building material with a thousand-year-old tradition – as the remains of the Greek fortification of Capo Soprano in Gela, Sicily, of 4th century B.C. show. It is also shown by Middle Eastern cities entirely built with soil as Shibam in Yemen (16th century) also known as the Manhattan of the Desert; by virtue of its versatility, this city is able to be in perfect balance with the environment: the earth lends itself to results accessible to any productive organization, from the simplest to the most complex. Moreover, it is an easily available resource in most geographical areas and the variety of the performances achievable through different executive techniques allows to produce artifacts suitable to pursue energy saving and comfort in different climatic contexts (Sposito, 2013). The characteristics of rammed earth include: high thermal inertia (due to its hygroscopic properties); the ability to maintain a constant humidity level of about 50% in indoor environments, thus avoiding humidity levels higher than 70%, responsible for mould (Arundel et alii, 1986) or the proliferation of mites and asthmatic diseases (Howieson, 2005); the different properties of acoustic insulation (linked to the 'elasticity' of the material), of electromagnetic wave reduction higher than all other construction materials (thickness of only 15 cm with soil around 99%), of air purification (thanks to the high porosity of the material that absorbs water vapour) and to eliminate condensation phenomena, especially interstitial condensation. The high maintainability, the effect of water and the compressive strength are its weaknesses.

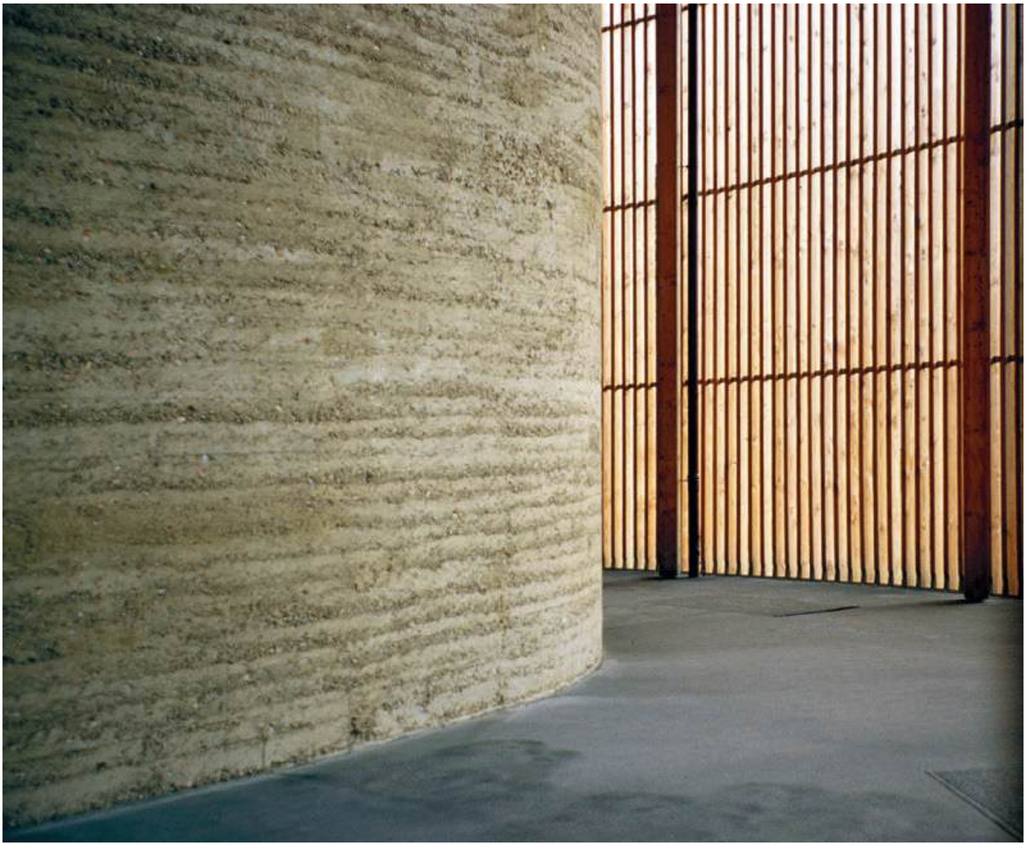
6.1 - The NK'MIP Cultural Centre in Canada (credit: www.
nkmipdesert.com).

Among the most widespread products attributable to rammed earth there is certainly adobe, a hand-compacted brick, with a mould and without compression, and left to dry naturally. Among the most used, especially in recent times, we should mention the compressed block, a brick made with the aid of mechanical presses to increase the compression characteristics, and the extruded block, whose creation is similar to that of bricks. Another widespread construction technique is the pisé, which consists in moulding and compressing the soil in special formworks: the material is placed in layers of 5-12 cm and trod until it reaches layers of about 80 cm. The peculiarities of rammed earth, on the one hand, lend themselves to the creation of new highly sustainable artifacts, thanks to the plastic and iconographic potential of the material. On the other, they are extremely useful for interventions of integration in ancient soil buildings, eliminating any incompatibility – both physical and on identity – caused by modern materials. For these reasons, some contemporary enlightened designers have ventured into rediscovering the sustainability characteristics of rammed earth by preferring the soil to other materials having line and more energy-consuming production processes.

Rammed earth has been used in many building types such as museums, schools, hotels, villas, especially in countries such as Australia, Canada or the United States, where regulations and standards for this building material exist since a long time. The NK'MIP Cultural Centre [Fig. 6.1] has been made in Canada, British Columbia, in an area belonging to Osoyoos Indians, marked by a peculiar habitat of the Canadian scenario. To the initial projects, by Hotson Bakker Boniface Haden Architects + Urbanistes (HBBH), made up of a cement building, a pisé wall has been added. It was made with local soil, colouring and a percentage of cement of just over 6% – to better integrate with the surrounding environment and meet the needs of the Indian community that struggled to identify with concrete buildings. In geographical contexts characterized by desert areas, integration with the surrounding landscape can only be achieved through the use of natural materials such as soil. The following examples should be seen in this perspective: the 1997 Dirt House in Scottsdale, Arizona, a one-story residential building by architect Neil Jones (Rael, 2008), the Palmer-Rose House in Tucson, Arizona, designed by the architect Rick Joy in 2001 with pisé walls – the same technique used for the hall at the McDowell Sonoran Preserve – and The TarraWarra Museum of Art [Fig. 6.2] in Victoria, Australia, entirely made in soil in 2004 by architect Alan Powell. SanBaoPeng Art Museum (2017) in Jingdezheng, China, is more recent. A project by DL Atelier, that uses local rammed earth to delimit with 150 m long and 4 m high partitions, the exhibition space, recalling, through the use of clay, the material with which the exposed ceramics are made. The two longitudinal partitions delimit the exhibition areas together with large transversal windows and allow the new architecture to integrate with discretion in a markedly naturalistic setting.

In Europe, Martin Rauch is considered one of the pioneers of the modern techniques to apply traditional methods of building with soil. The Austrian architect has made a clay volume in the Chapel of Reconciliation in Berlin [Fig. 6.3], inaugurating the first German Church in compressed clay (from 30 to 8 cm) with walls 60 cm thick and 7 metres high. The building is situated on the ruins of the old Church built in 1894, fallen into ruin after the construction of the Berlin Wall. The new project is made up by two elliptical buildings, placed one inside the other but with the main axes rotated orthogonally: the external oval is made of wooden plates while the inner one is made of compressed clay, mixed with fragments of stone and glass from the rubble of the previous church. The experimentation with rammed earth started by Martin Rauch in 1994 with the creation of his Atelier in Schlins, Austria [Fig. 6.4] – which became a reference building for the professionals – and continued with several residential buildings. The Atelier, designed with the architect Roger Boltshauser, is a three-story building, made in compressed earth stratified with thin rows of bricks arranged in regular intervals, visible in the façade. The walls, the floors and the plasters are made entirely with the soil of earthworks, the result of the will to build a house only with sustainable materials. The soil house has a monolithic structure that looks like a sculpture block, abstract and artificial nature pushed upwards by the earth below. Finally, it is worth mentioning the new Ricola Kräuterzentrum in Laufren, Switzerland, a project by Herzog & de Meuron with the Lehm Ton Erde Baukunst GmbH (of Martin Rauch), bio/green manifesto of the well-known company producing

6.2 - The TarraWarra Museum of Art in Victoria, Australia (credits: www.museumnetwork.sothebys.com/en/museums/tarrawarra-museum-of-art).



6.3 - The Chapel of Reconciliation in Berlin by Martin Rauch (credits: Minke, 2000).

6.4 - The Atelier in Schlins, Austria, by Martin Rauch and Roger Boltshauser (credits: netzwerklehm.at/lehmbau/haus-rauch/).

6.5, 6.6, 6.7 - The materials used in the experimentation:
Earth; Sand; Halloysite (credits: Scalisi and Sposito, 2017).

aromatic herbs, that has always cared about environmental sustainability. The envelope – made with a mix with local soil, volcanic tuff aggregates from quarries within 8 km and lime – allows to integrate the structure with the surrounding landscape and, at the same time, to mitigate the operational energy consumption, helping to stabilize the temperature and humidity levels necessary for processing the herbs.

6.3 Low-Impact Stabilization Strategies

The scarce mechanical characteristics of rammed earth require, in order to be used in the artifacts, to subject it to a stabilization process that modifies the physico-chemical and mechanical properties of the earth-water system so that, by adding other materials, their strength and/or other properties can be improved for a long-lasting and compatible use for specific uses. The stabilization process of the soil has ancient origins in the building with rammed earth tradition, by adding vegetable or animal fibres (straw, horsehair), glue substances (casein, blood, animal dung, egg whites), cements, lime or bitumen (Danso et alii, 2015) made with mechanical, physical and chemical procedures (Houben and Guillaud, 1994). The first one involves the compacting of the earth, an action that modifies its density, mechanical strength, compressibility, permeability and porosity; the second one is performed with mixtures of different grain sizes and controlled by specific sieves; the third one, discussed in this section, is the addition of other materials or chemical products. The scientific literature gives a fairly thorough picture of the researches and experiments that, in the last fifteen years, have provided for the use of different types of stabilizers (artificial, natural and mixed) to improve the mechanical performance of rammed earth.

Among the artificial stabilizers, cement is definitely the most used mostly for the proportional correlation between compressive strength and its dose in the mix (Morel et alii, 2007): the experiments that have produced rammed earth bricks with compressive strength of 9.4 MPa (Walker and Stace, 1997), of 6.5 MPa (Bahar et alii, 2004), of 6.4 MPa (Millogo and Morel, 2012) are different. Another tested stabilizer is lime, with which rammed earth bricks have been created, having a compressive strength between 3.03 MPa (Burroughs, 2006) and 3.6 MPa (Millogo et alii, 2008). If the aforementioned experiments show that the two artificial stabilizers significantly improve the compression performances of rammed earth (whose environmental impact is irrelevant), it is also common opinion that cement and lime are anything but 'sustainable' and 'ecological' materials, since they have a high embodied energy. Therefore, this awareness has driven new experiments with the aim of determining the maximum percentages of cement and lime useful for improving the performance of the new mix at the same time mitigating its environmental impact (Ciancio et alii, 2014). Therefore, it was calculated that the maximum percentage of cement and lime to use – with reference to the energy impact of autoclaved aerated concrete (AAC) which is one of the lowest environmental impact materials among those cement-based – is equal to 8% for the first and 7% for the latter (Maskell et alii, 2014a). Actually, even with smaller percentages it is possible to have satisfactory performances: adding 5% of cement, in fact, gives a compressive strength equal to 7.4 MPa, definitely not an insignificant value compared with 2.9 MPa of minimum compressive strength in dry conditions (Maskell et alii, 2014).

Other studies focused on the stabilization of rammed earth using cement or lime mixed with materials of natural origin such as Sugarcane Bagasse Ash (SBA) – a fibrous residue obtained from the sugarcane after extracting the juice. SBA and ordinary Portland cement, 8 and 10 percent respectively, can provide a compressive strength of 5.85 MPa (James et alii, 2016). Other experiments with the Sugarcane Bagasse Ash as a stabilizer were carried out by Sofia Lima (et alii, 2012), Richard Onchiri (et alii, 2014), Ramadhan Salim (et alii, 2014), Anil Pratap Singh and Piyush Kumar (2015), and Pakdee Khobklang (et alii, 2008). Another interesting research deals with the use of cement and lime with metakaolin, a 'natural' and 'sustainable' pozzolanic binder obtained by calcining the kaolinitic clays at a temperature of about 650 °C. The bricks are made by adding 5% of lime and 5% of metakaolin and have reached a compressive strength of 6.96 MPa while samples with the same percentages of cement and metakaolin have values of 3.73 MPa (Maskell et alii, 2015, 2016).

Finally, among the many studies that have used only natural stabilizers, prompted by a urgent sensitivity towards the ecosystem and recalling an already consolidated practice since ancient times, it is to be noted that many of them have experienced alternative additives, waste or by-products coming from different industrial sectors (Oti et alii, 2009; Tingle et alii, 2007). The different stabilization with Hibiscus cannabinus fibres make relevant examples – compressive strength equal to 2.9 MPa (Millogo et al., 2014), with tea processing waste – compressive strength of 7.6 MPa (Demir, 2006), with fruits of palm oil waste – compressive strength of 10.65 MPa (Ismail and Yaacob, 2011), with cassava skins – compressive strength of 2.15 MPa (Villamizar et alii, 2012). It is also worth mentioning a study that has experimented with the use of alginate (a natural polymer extracted from a marine algae) and sheep's wool to stabilize soils and to produce a sustainable, non-toxic and local composite building material (Galán-Marín et alii, 2010). Tests have shown that if adding alginate in the mixture increases the compressive strength to 3.77 MPa and that if adding wool increases the compressive strength to 3.05 MPa, when combined they significantly improve the resistance up to 4.44 MPa, a similar value to that obtained with 10% of Portland cement and greater than the result obtained with the highest percentages of lime (3.6 MPa).

6.4 Green Nanotech for Earth: Halloysite as a Design Enabler

Below is the experimentation on rammed earth and nanotechnologies carried out by Francesca Scalisi and Cesare Sposito at the University of Palermo in 2017-2018. The experimental research was carried out with the aim of improving the performance of rammed earth bricks with the help of nanotechnologies, creating a 'new material' with reduced embodied energy and low CO_2 emissions into the atmosphere. Specifically, the analysed performances are related to the compressive strength that expand their area of use as a building material.

Materials, Methodology and Operational Stages –The rammed earth is a natural composite material originating from the combination of several materials (clay, sand, etc.) whose characteristics can be improved – through a stabilization process – by adding other materials. In this case, to the mix made up by soil [Fig. 6.5], sand [Fig. 6.6] and water we decided to add Halloysite [Fig. 6.7], a clay nanotube. This solution was supported by the bio-based nature that the nanostructured material guarantees and the performance potential that nanotechnology, in general, gives to the building sector (Scalisi, 2010).

About the materials in the mix it should be noted that:

a. earth and sand were supplied by the Guglielmino Company in Misterbianco (CT) and come from the quarry called Roccasieli-Guglielmino Group, located in the Municipality of Motta S. Anastasia (CT);
b. the chemical composition of the soil is listed in Table 6.1;
c. the chemical composition and the granulometry of sand are shown respectively in Tables 6.2 and 6.3;
d. the Halloysite Nanoclay used for this experimentation, whose characteristics are listed in Table 6.4 is produced by Applied Minerals Inc. and is available at Sigma-Aldrich.

The Halloysite is a clay nanotubes with a diameter generally under 100 nanometres and with lengths ranging from about 500 nanometres to over 1.2 microns; it is chemically similar to kaolinite (Yuan et alii, 2015) and has a predominantly hollow tubular structure with a double layer of aluminium, silicon, hydrogen and oxygen. Not expensive, readily available and non-toxic material with high mechanical resistance (Farzadina et alii, 2013), the Halloysite – together with nanocomposites and nanometric powders – is part of a 'green nanotechnology' sector which aims to develop safe and ecologically less polluting products (Kamble et alii, 2012; Nasrollahzadeh et alii, 2019). Halloysite nanotubes have many commercial applications such as polymer and plastic additives, electronic components, drug delivery vehicles, cosmetics and household products (Lvov et alii, 2008; Zhang et alii, 2016; Lazzara et alii, 2018), being inorganic materials for reinforcement. In general, adding 5% of Halloysite synergistically

	[%]
SiO_2	48.88
Na2O	1.33
K2O	0.56
MgO	5.05
$Fe2O_3$	8.08
$Al\ 2O_3$	11.8
MnO_2	0.05
TiO_2	0.05
Organic matter	2.03
Cl	0.013
F	0.001

Tab. 6.1 - The chemical composition of the earth used in the experimentation.

	[%]
SiO_2	92
Al_2O_3	4
Fe_2O_3	0.04
TiO_2	0.01
CaO	0.3
MgO	0.02
K_2O	3.2
Na_2O	0.2

Tab. 6.2 - The chemical composition of the sand used in the experimentation.

mm	[%]
>1.00<1.50	3
1.00 - 0.80	8
0.80 -0.60	37
0.60 - 0.40	37
0.40 - 0.30	8
<0.30	5

Tab. 6.3 - Particle size of sand used in the experimentation.

Dimensions	30-70 nm diameter × 1-3 μm length
Pore size	1.26-1.34 mL/g pore volume
Surface area	64 m2/g
Capacity	8.0 meq/g cation exchange capacity
Density	2.53 (true specific gravity)
Formula	H4Al2O9Si2 · 2 H2O
Molecular Weigth	294.19 g/mol
Form	nanopowder
Color	75-96 Hunter Brightness
Refractive index	n20/D 1.54

Tab. 6.4 - Characteristics of Halloysite Nanoclay.

		Sample 1	Sample 2
Weight of sample	[g]	576.32	576.03
Weight in air of sample in paraffin	[g]	613.62	603.77
Weight of paraffin	[g]	37.30	27.74
Bulk weight of paraffin	[g/cm3]	0.90	0.90
Volume of paraffin	[cm3]	41.52	30.88
Net weight in water of sample in paraffin	[g]	294.32	293.42
Effective volume	[dm3]	277.78	279.47
Density	[g/cm3]	2.07	2.06
Mean density	**[g/cm3]**	**2.07**	

Tab. 6.5 - Bulk Weight of Samples.

Samples	Dimensions			Section	Mass	Tensile Strenght	Compressive strength
	a [mm]	b [mm]	c [mm]	(axb) [mm^2]	[gr]	[N]	[MPa]
C1	50.8	50.7	50.8	2576.1	266	8439	3.3
C2	50.4	51.1	51.0	2571.4	268	8550	3.3
C3	50.0	50.4	51.9	2518.0	262	9309	3.7
C4	51.4	51.6	51.5	2651.7	277	9081	3.4
C5	51.0	51.4	51.4	2621.4	270	8712	3.3
C6	51.0	51.3	51.5	2616.3	273	10245	3.9
Average compressive strength 3.4 Mpa | difference 0.3 | coefficient of variation 8.0%							

Tab. 6.6 - The results of compressive strength tests.

6.8, 6.9, 6.10, 6.11, 6.12, 16.3 - The materials used in the experimentation: Earth; Sand; Halloysite (credits: Scalisi and Sposito, 2017).

increases the strength of the polymer by 30-70% and improves its total adhesiveness (Lvov and Elshad, 2013).

The different materials (47% soil, 30% sand and 2% Halloysite) have been dry mixed and then water was added amounting to 21% of the weight. To create the samples, the consolidated procedure used for the adobe was followed: the rammed earth brick was hand-moulded, with 50x50x50 mm steel moulds, without mechanical compression but completely filling the cavities and removing the excess material. Once the mould was rotated and the block was extracted, the elements obtained have been placed on a shelf in a dry and ventilated place to allow them to dry. After a couple of days, they seemed solid enough to be turned and kept to dry – which lasted 28 days. While preparing the samples, two tests were necessary, before the final one, to determine the percentage of Halloysite to include in the mix: the first with 5% of Halloysite, the second with 3%. Both mixtures were excessively fluid, regardless the quantity of water used, pushing to reduce the percentage of Halloysite up to 2%, used for the production of the final samples. The samples obtained have undergone compressive strength tests. In the absence of specific regulations on rammed earth products, the UNI EN 772-1:2011 standard was used 'Methods of Test for Masonry Units – Part 1: Determination of Compressive Strength', also used in other experiments on this material (Maskell et alii, 2014). In our case, this Standard was used as a reference for the testing methods with modifications on the 'conditioning of the samples for the compressive strength tests'.

Before performing compressive strength tests, the samples were prepared with cutting and grinding operations and by being changed and conditioned at a temperature of 20±2 °C and at a humidity of 65±5%, up to constant mass. Furthermore, the bulk weight of some sample fragments (2 determinations per series of samples) was established using the hydrostatic weighing method (C.N.R. reference standard – B.U. n. 40), since the calculation with the geometric method was not reliable, due to the irregularity of the samples [Tab. 6.5].

Results, Debate and Future Developments – The samples subjected to the compressive strength test are 6, labelled with the acronyms C1, C2, C3, C4, C5 and C6 [Figg. 6.8-6.13]. The results of each sample are listed in Table 6.6 that shows an average 'dry' compressive strength of 3.4 MPa. This is a satisfactory outcome, considering that in this new product stabilizers such as cement or lime were not used and that the minimum compressive strength under dry conditions is equal to 2.9 MPa (Maskell et alii, 2014). The value obtained is lower than that of the brick made with alginate and sheep's wool which has a compressive strength of 4.4 MPa (Galán-Marín et alii, 2010) or of the brick made with 5% cement and 5% metakaolin whose compressive strength is 3.73 MPa (Maskell et alii, 2015, 2016). But it is necessary to make some considerations: a) in both cases, the mixtures use more energy-intensive creation processes such as mechanical compaction (in case of alginate and wool mix) or extrusion (in case of metakaolin and cement mix); b) the bricks made with mechanical compaction and the extruded ones provide, even without stabilizers, greater resistance than the adobe; c) in the second case, the compressive strength is slightly higher – 3.4 and 3.7 MPa – even though it is an extruded brick with 5% cement in the mix.

Therefore, the research carried out has interesting margins for improvement. First, on the introduction of mechanical compression, considering that by using rammed earth, currently, a handmade brick is unrealistic: the introduction of mechanical means in production, although it increases the embodied energy (which is still lower than that of other materials), it improves both the mechanical performance and the rammed earth production cycle. Furthermore, since the material is fragile under humid conditions, it will be necessary to check that the compressive strength in 'humid' conditions is not under 1 MPa, result of the tests performed by Maskell (et alii, 2014). Finally, since the Halloysite used in this experimentation is already on the market but, given its tubular shape, possible research developments – in a multidisciplinary perspective – may concern interventions aiming at loading the clay nanotubes in the laboratory, for example with biopolymers, and therefore use modified nanotubes in the mix.

6.5 From Material to Project: Skills, Culture & Policy for Ecological Design

Since the environmental issue is a top priority, it is clear that the relationship between Project and Matter must regain a central role, despite the complexity of the set of requirements established by the modern era, especially considering the environmental aspects of the life cycle. In this sense, the figure of the Architect-Technologist as a qualified operator is decisive. He, by regaining possession of an often forgotten 'material' knowledge, should be able to manage the project with the awareness of the material and productive dimension of the processes, smartly and 'laically' manning technologies and incisively carrying out his cultural and professional role; «[...] a designer aware of the material and productive dimension of the processes: an architect able to dialogue with specialists (without being such), to translate figurative options, spatial configurations and fruitive needs in precise technical specifications and in coherent, efficient and sustainable construction devices, without losing an overview of the whole architectural design, as a cultured synthesis of eclectic and complementary knowledge» (Antonini et alii, 2018, p. 17).

Over the last twenty years, the industrial and commercial dynamics of technological innovation driven by the demands imposed by the pressing environmental issue have influenced materials, techniques and construction technologies invalidating established practices. These techniques considering reduced emissions, containment of operational energy consumption and ecological products, have produced artifacts often without identity «[...] with a value that is more identificatory than stylistic, [...] 'symbolic buildings' with two essential components: being 'symbols' in the urban confusion that surrounds them, but also that of replacing the 'modest' monuments of the past» (Dorfles, 2007, p. 8). The research carried out over the past few years on rammed earth responds, in this sense, to the twofold request, on the one hand, to evaluate and design bio-based materials both from a technical performance point of view and mostly with respect to environmental performance, optimizing resources and production processes in order to reduce the most energy-intensive stages. And on the other hand, to make architecture recover its identity through coherence, language recognizability and relationship with places.

The cultural resistance to this material is part of the 12 obstacles wisely identified by Amr Sourani and Muhammad Sohail (2011) on the implementation of sustainable construction forms. We do not know how much the illustrated experimentation can contribute to overcoming prejudices on this material – definitely humble but sustainable and with performances that can be enhanced with the help of 'green nanotechnologies'. But we are sure that, today more than ever, a radical shift in the behavior of operators in the building sector is necessary (Francese, 2014). And what shouldn't also be delayed is: in-depth analysis of regulatory tools, incentives and financing tools, training and skills development, changes in users' behaviours and social practices for which the facilitation dialogue encouraged by the United Nations with the Talanoa Dialogue Platform and the United Nations Framework Convention on Climate Change in 2018 – and its common formal review scheduled in 2023 – can be a good fly-wheel, bridging the gap between climate ambitions and current policies in the building industry.

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Series
Alleli / Research - n. **269**

ISBN 979-12-5644-164-8

First edition December 2025

Realizzato con il contributo dei fondi di ricerca dell'Università degli Studi di Palermo.
The book is funded by contributions from the University of Palermo's research funds.

Graphic design: Ilaria Valenti
Font: Calluna, Strawford
Print: tipografia TheFactory, Roma

LetteraVentidue Edizioni Srl
Via Luigi Spagna, 50P - 96100 Siracusa

www.letteraventidue.com

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