Circular Design and Material Regeneration: The STONE Project as a System Paradigm in the Stone Industry

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Abstract
This contribution aims to investigate the strategic role of design within the ecological transition and the circular economy, through an in-depth analysis of the STONE project. The latter represents an advanced operational model for the reuse of stone waste within local supply chains with high environmental impact, promoting the design of sustainable architectural components capable of generating cultural, aesthetic, functional, and economic value. The paper, structured in multiple sections, explores the dimension of systemic design, the potential of digital and additive technologies, the hybridization between artisanal knowledge and scientific know-how, as well as the ability of the STONE project to activate new practices of co-design and social inclusion. The objective is to offer a methodological and operational framework that can be exported, capable of stimulating responsible innovation and the creation of resilient and regenerative production systems.

Keywords
Circularity
Regeneration
Systemic Design
Parametric Design

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BACKGROUND

In a time marked by increasingly evident environmental crises, the growing scarcity of natural resources, and the instability of global supply chains, design emerges as a key discipline in redefining production models. It is no longer just about shaping objects, but about rethinking entire systems of production, distribution, and use, orienting them towards regenerative logics capable of generating environmental, social, and economic value. In this context, design evolves from a formal gesture into a systemic and cultural tool, able to connect materials, technologies, skills, and relationships. This transformation implies overcoming the linear logic — extraction, production, consumption, disposal — in favor of circular models that, through design, can reduce impacts and multiply possibilities for reuse, recovery, and transformation. Design, understood in this way, is configured as a relational practice that integrates scientific knowledge and tacit know-how, material knowledge and symbolic dimensions, acting as a mediator between territories, cultures, and visions of the future (Antonelli, & Rawsthorn, 2022).

The stone sector, long associated with values of solidity and durability, today appears as one of the paradigms of this tension between value and waste. Its ecological footprint, linked to the production of enormous quantities of waste materials — slurry, sludge, debris — requires deep reflection: is a model still sustainable that values only a small part of the extracted material, leaving the majority to be dispersed or abandoned? It is precisely in response to this contradiction that the STONE project (SusTainable ecOdesign reusiNg quarring wastE) was born.

Developed within the Extended Partnership MICS — Made in Italy Circular and Sustainable — and supported by the National Recovery and Resilience Plan (PNRR), the project brings together universities, research centers, companies, and local communities in a shared and multidisciplinary path aimed at regenerating the stone sector through collaboration between design and disciplines such as materials chemistry and technical architecture, in order to investigate multiple circular scenarios in various application sectors. The core of STONE lies in its ability to reinterpret quarry and processing waste as new project material, transforming what is excluded into an aesthetic, technological, and social opportunity.

Through a systemic perspective, the project aims to build an alternative and resilient supply chain based on the integration of technological innovation and local knowledge, modular production and digital processes, parametric design, and material languages. STONE presents itself as a territorial laboratory where design not only restores meaning to materials but activates local economies, renews design languages, and promotes a new culture of reuse, responsibility, and identity.

The need to address the issue related to large quantities of stone waste through the formulation of circular production scenarios is particularly felt in Italy, which, with its production districts specialized in natural stone processing, represents one of the main European and extra-European players in the stone market. However, this economic centrality is accompanied by a significant environmental impact. Data show that over 70% of the extracted material is discarded in the form of debris, dust, and sludge from sawing. These materials, rarely reintegrated into production cycles, constitute a critical issue both in terms of disposal and lost added value. Moreover, extraction and processing processes present serious energy inefficiencies, obsolete production structures, and uneven regulations.

In this scenario, the STONE project introduces a paradigm shift: from extractive linearity to the circular economy, activating resilient local supply chains founded on new design and production models. Numerous applications deriving from experiments on the use of stone waste for the production of new materials and products are present in literature and business practice (Scioti et. al., 2024; Fatiguso et al., 2025; Baccaro et al., 2024; Scioti et al. 2025), as well as some sustainability assessments through Life Cycle Assessment (LCA) analyses. In particular, some studies have shown that slurry, which the STONE project mainly focuses on, can be used as a partial substitute for cement or fine aggregate, being comparable in granulometry to filler for the production of concrete and mortars. In fact, slurry has been used in the production of thermopolymers for fused deposition modeling (FDM) 3D printing (Esposito Corcione et al, 2018).

However, only a limited number of academic and business works have ventured into designing products made from these materials intended to be disassembled and reused. Indeed, one of the project's objectives is the definition of Proofs of Concept (PoC) for furniture and construction products that can meet requirements of modularity, durability, disassembly, and component reuse in other contexts, even with different functions. These circular economy strategies were chosen because materials containing inert and non-renewable resources, such as stone waste, do not allow for complete biodegradability, even in the case of thermopolymers using Polylactic Acid (PLA) (Almansoori, & Pervaiz, 2023).

In this regard, the contribution aims to define the methodological flow that enables design choices related to the formal and functional design of modular components, regardless of the material type, used for the first time in a specific context and function, then dismantled and reconfigured at the end of life in another context and function. Among the physical implementation strategies of the circular economy is the generation of a digital twin of the product, both to ensure a longer and more sustainable life cycle and to make the element more responsive to consumer needs; therefore, these are equipped with performance monitoring sensors. Fig. 1

METHODOLOGICAL FRAMEWORK

The development of innovative scenarios within complex systems such as the stone supply chain begins with an investigation based on a systemic design approach that examines the supply chain to promote sustainable design practices for new value chains. To achieve the research objectives, the traditional stone supply chain was first analyzed in the three project-specific geoclusters through the “systemic design” approach, which does not limit itself to considering a single object or process but embraces a broad and integrated vision capable of grasping the complexity and interdependencies of production systems as a whole. In this sense, systemic design functions as a truly holistic lens through which to interpret and intervene on the multiple dimensions — technological, social, environmental, and regulatory — that define the project context.

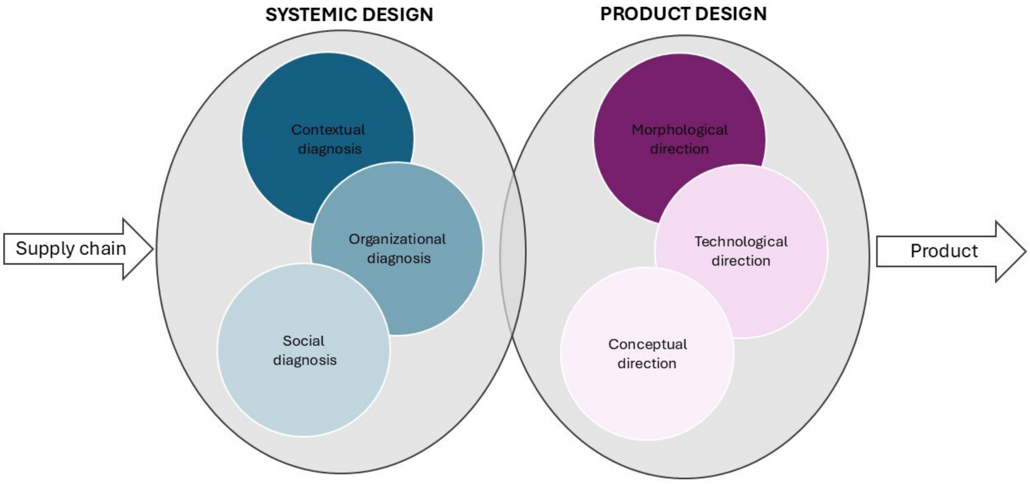

Fig. 1
Methodological Framework

Systemic design starts from a holistic diagnosis phase composed of qualitative and quantitative observation of the contextual, organizational, and social framework of the territory involved in the traditional supply chain, in this case, the stone districts of the three geoclusters.
The first phase focuses on the analysis of the existing context (Contextual Diagnosis). The second phase examines energy and material flows (Organizational Diagnosis), while the third phase investigates the social framework (Social Diagnosis). These activities are structured so that the data and observations gathered — through documentary research and fieldwork — can be used to identify key problems and opportunities. This foundation supports the development of a systemic project, ultimately leading to the design of sustainability scenarios (Battistoni et al. 2019; Aulisio et al., 2023).

Building on the systemic design approach, an additional operational workflow is articulated, oriented towards the design definition of products related to the new production chain. This workflow acts as a coherent continuation of the systemic methodological framework and unfolds through a multidimensional investigative path branching along three main axes: “morphological”, “technological”, and “conceptual”. Each exploratory direction contributes interdependently to the identification and configuration of the elemental component of the system-product, understood as the founding and recursive unit of the overall project.

The first axis, morphological in nature, is aimed at exploring new formal and linguistic configurations of the material, with particular attention to its expressive and generative potential. This approach seeks to reinterpret the intrinsic structure of the material — in this case, stone — as an active matrix of form, capable of giving rise to novel solutions through experimental design practices and morpho-typological abstraction processes. The material is thus investigated not only as a support but as a creator of meaning and a semiotic device.

The second axis, technological in character, focuses on the critical analysis and advanced development of material transformation processes, including emerging technologies, innovative treatment methods, and reuse strategies. Particular emphasis is placed on the hybridization of stone with other materials and its use in recycled form to enhance its functional, structural, and environmental performance. This operational axis fits within the broader framework of systemic sustainability, promoting high-tech, low-impact design solutions.

Finally, the conceptual axis assumes a speculative and strategic perspective, where design is configured as a reflective and anticipatory practice. In this realm, the material is interrogated not only in its operational dimension but also in its cultural meanings, environmental impacts, and social repercussions. The project thus becomes a place of meaning, capable of problematizing the relationship between material innovation, changes in production paradigms, and transformations in life models, placing a systemic and responsible vision of design practice at the center.

To reach the objective, examples and design references were analyzed and cataloged based on their morphological and technological characteristics, useful for defining conceptual references. The case studies analyzed should not be interpreted as replicable models or as mere applications of recycled materials aimed at reproducing existing products. On the contrary, they should be understood as design stimuli, open hypotheses, capable of triggering critical reflection on the role of design tasked with shaping new meanings and developing technologically innovative solutions in defining new production and cultural paradigms and responding to ongoing structural changes. Through the integration and dialogue between design and other scientific disciplines — from materials science to environmental engineering, from sociology to the circular economy — fertile ground is created for the emergence of radically innovative technological solutions that not only respond to contemporary challenges but are also able to anticipate and shape sustainable future scenarios.

MORPHOLOGICAL REFERNCE

The first research direction focuses on exploring new application scenarios for stone material through the morphological and functional analysis of living organisms and their structures. This approach is inspired by the principles of biomimicry, a discipline that studies the evolutionary processes of nature to transfer efficient, adaptive, and sustainable solutions to the fields of design and materials engineering.

The organisms analyzed have evolved over time by developing survival strategies highly contextualized to their environment, maintaining a dynamic balance with natural cycles. These biological strategies, often based on complex forms, optimized geometries, and symbiotic relationships with the ecosystem, represent a valuable source of inspiration to rethink stone material not only as a construction element but as an active component of broader design systems capable of interacting with the environment and contributing to regenerative development models.

The goal is not to literally replicate nature but to translate its morphological and adaptive principles into design criteria applicable to the processing, transformation, and use of stone material, thus directing innovation toward functional, sustainable, and contextually aware solutions (Langella, 2019).

Examples include projects like SADAF – RTA 3D Printed Bus Stop by MEAN* Studio, an urban bus shelter created using 3D printing and inspired by shells found on the beaches of Dubai. The shelter is designed to be printed in pieces that fit within the build volume of industrial 3D printers. Each piece is unique and connects to its neighboring parts to easily assemble the structure.

Another example is the Adaptation Chair by designer Joris Laarman, a chair composed of long vertical cells that start from the bottom as legs and transform their geometry to meet the needs of different areas of the chair. The legs branch into smaller legs, which then branch again to support the structure, on top of which the seat rests.

TECHNOLOGICAL REFERNCE

The second research direction focuses on developing new application scenarios for stone material through the use of advanced tools from contemporary design, particularly those offered by generative design, parametric design, and Industry 4.0 technologies.
In this context, design methodologies based on algorithmic and computational processes have been explored, capable of generating complex and efficient solutions starting from a set of defined constraints and parameters. Generative design, in particular, is an iterative approach that leverages the integration of parametric modeling, artificial intelligence, and cloud computing to explore a wide range of design alternatives quickly and with a high degree of optimization.

Using these tools, it is possible to study and develop new structural configurations, joint systems, and construction components for stone materials, overcoming the limitations of traditional techniques and paving the way for more efficient, adaptive, and digitally controlled production methods. Integration with Industry 4.0 technologies — such as additive manufacturing, advanced robotics, and automated production — enables the creation of custom-designed elements optimized for performance, physical constraints, and sustainability, with a level of precision and complexity previously unattainable.

This research direction does not merely aim to replace conventional construction methods but seeks to define a new design paradigm in which stone material is reinterpreted in a contemporary key, becoming an integral part of intelligent, adaptive, and digitally guided systems.

Examples cited in the research include the Programmed Wall by the Gramazio Kohler Research Unit - Immersive Design Lab at ETH Zurich. The programmed wall is a brick wall constructed using an industrial robotic arm. For bricklaying, a robotic arm designed at ETH Zurich by Swiss architects Fabio Gramazio and

Matthias Kohler was used. The robotic arm laid over 400 bricks in a unique pattern without optical references or measurements—i.e., without additional effort—forming a contorted profile. The arm was controlled by a custom-developed algorithmic design tool that informed the robot of the spatial arrangement of the bricks according to a procedural logic.

Another example is Fabric Form by designers Ron Culver and Joseph Sarafian, who developed a method to cast concrete into Lycra stretched by a robotic arm, used to create radically new architectural forms. Developed at the University of California, the Fabric Cast Concrete project involves pouring a fiberglass concrete mixture into Y-shaped Lycra sleeves, stretched by six-axis robots.

Again, this research draws on technological references to understand how innovative systems can enhance the material, aiming to explore the appropriate translation of some of these systems into architectural and design practice.

CONCEPTUAL REFERENCE: SUSTAINABILITY, SEMIOTIC POLLUTION, AND CONTEXTUAL CUSTOMIZATION

At the core of the STONE project lies a critical reflection on the foundational values of sustainability, understood not only in environmental terms but also cultural, communicative, and systemic dimensions. Two key concepts have guided the research path: "semiotic pollution" and "contextual customization". These elements serve as interpretative and design tools to tackle the challenges posed by the circular economy and the complexity of contemporary ecosystems.

The concept of "semiotic pollution" refers to the excess of visual and formal stimuli that often accompanies the uncritical application of technologies in design. Current examples in the design landscape, despite demonstrating technologically sophisticated results, risk saturating the design language, creating communicative confusion and loss of meaning. This phenomenon occurs when technology is treated as an end in itself, rather than as a means to consciously and purposefully respond to the real needs of people and the environment they inhabit.

In contrast to this aestheticizing and self-referential drift, the project proposes an approach based on "simplification" as a design value — understood not as a reduction of complexity but as the ability to interpret and organize complexity through essential, effective, and coherent solutions. Designing with a circular economy mindset means adapting technologies, forms, and processes to the specific context — geographic, cultural, productive — avoiding standardized solutions detached from the reality in which they must operate.

From this stems the second methodological pillar: careful customization related to the territory and its specificities, which goes beyond mere aesthetic personalization and is founded on relational and situated design, capable of responding to local needs through materials, technologies, and processes consistent with available resources and the identity of the place.

In a world characterized by increasingly interconnected and complex relationships, the designer's task is no longer to add form but to remove the superfluous to restore meaning. The real challenge is to outline credible, sustainable, and intelligent scenarios that integrate functionality, ethics, aesthetics, and environmental impact. In this sense, design simplification proposes itself as a guiding principle for sustainability: less material, less energy, less formal noise, but more meaning, adaptability, and awareness.

RESULTS

HOLISTIC DIAGNOSIS OF THE MARBLE DISTRICT IN TUSCANY

The marble extraction activity represents a distinctive and strategic element of the Apuo-Versilian district, making it one of the most vital local production systems within the Italian stone sector. This district is notable not only for its historical relevance but also for leading the country in terms of the number of extraction companies and the value of exports (Legambiente, 2019). Geographically, the Apuo-Versilian area encompasses eleven municipalities: Ortonovo, Carrara, Fivizzano, Massa, Minucciano, Montignoso, Piazza al Serchio, Pietrasanta, Seravezza, Stazzema, and Vagli di Sotto, which fall within the provinces of Massa-Carrara and Lucca. These municipalities collectively form a core region for marble quarrying and processing. The economic significance of this area is considerable. According to estimates made in collaboration with sector experts, the economic value generated in the province of Massa-Carrara alone ranges between 2,500 and 3,000 thousand euros, and between 4,500 and 5,400 thousand euros across the entire district. Employment data further highlight the industry's impact, with approximately 8,000 individuals employed both directly and indirectly in the sector, of which around 5,000 are involved in quarrying and stone processing activities - representing roughly 9% of Italy's total employment in this field. Among the many stone products manufactured in Tuscany, Carrara marble is particularly noteworthy for being transported over the longest distances. In 2020, the province of Lucca exported cut, shaped, and finished stone goods worth €91 million. Although this figure represents a decline from the 2016 peak of €148 million (€108 million pre-Covid in 2019), it underscores the district's global relevance. Major export destinations include the United States, Qatar, the United Kingdom, France, and other countries in the Middle East. The primary applications for these stone products are in the construction sector, mainly for flooring and cladding, with a smaller percentage used in funerary art, urban furnishings, and bespoke architectural elements. Product-wise, the most common categories processed in the district are blocks (both rough and squared) and slabs (rough and polished), while thin tiles remain a niche product. Data from the Institute of Studies and Research (ISR) of Massa-Carrara reveal that the total volume of marble extracted from Carrara quarries in 2020 remained steady at approximately 2.8 million tons, with an additional 144,000 tons sourced from the Massa area. By 2022, stone materials accounted for 20% of total exports from the Massa-Carrara province, with processed stone contributing €417 million and raw stone €202 million to export revenues—a notable 17.9% increase from the previous year (Export Press Release 2022, Lucca, Pisa, Massa-Carrara). Despite this, only 46% of the extracted blocks undergo processing within the province itself, pointing to significant external processing and transport. The ornamental-use stone extracted in the province also forms a major portion of total stone output. In 2017, such materials exceeded one million tons, of which a substantial 92% was quarried in Carrara and the remaining 8% in Massa. A noticeable decline in production occurred in 2019 and 2020, primarily due to disruptions caused by the COVID-19 pandemic. As for quarry operations, the most recent available data from 2014-2015 identify 104 registered quarries in the province, with 82 located in Carrara and 17 in Massa. This accounts for over 72% of the entire Tuscan quarrying activity. To qualify as a quarry for ornamental materials, regulations require that at least 25% of the extracted material must be suitable for block production. This threshold, mandated by Article 20 of the PIT-PPR (Regional Plan for Landscape and Territory), is designed to ensure that quarrying remains focused on high-quality materials and to minimize debris.

However, compliance with this rule has been inconsistent. Numerous quarries continue operations despite falling below the 25% yield threshold. In fact, data show that 25 out of 80 quarries consistently produce yields under 10%. The rationale for the 25% benchmark is straightforward: no rational producer would intentionally reduce high-value blocks to low-value chips, so a low yield often indicates that extraction is taking place in geologically fractured zones, producing excessive waste (Legambiente, 2019). While processed marble generates the bulk of the sector's revenue, the by-products of cut materials should not be overlooked. Between 2001 and 2014, the share of blocks, semi-blocks, and irregular fragments reaching processing yards increased from 20% to 28%. The PR14 document, part of the Tuscan Regional Quarry Plan, presents future scenarios for extraction in the region. Prepared by IRPET, it utilizes production data from 2013 to 2016 to forecast long-term demand for extractive materials. Based on these data, a 20-year demand estimate of 41.6 million cubic meters was established. However, the plan curiously sets a "sustainable production" target of over 65.2 million cubic meters in the same period—57% higher than estimated demand. This discrepancy raises concerns about policy coherence and the potential environmental consequences of over-extraction. Article 20 of the PIT-PPR stipulates that extraction for industrial use must derive from ornamental materials and not solely serve inert material production. It explicitly states that inert production should be minimized to conserve resources and protect landscapes. Nonetheless, this principle has been broadly violated, as evidenced by the high number of low-yield quarries in operation.

Quarrying processes generate three principal waste categories: overburden (earth and rocks removed), ornamental stone, and processing waste such as marble sludge (marmettola). Environmental concerns arise from the volume and disposal of these wastes. For example, cutting a 24.3-ton block with a frame saw results in about 11.7 tons of sludge; with a diamond wire, 11.9 tons; and with a diamond blade, 13.5 tons. Marmettola, along with residual quarry soils, can cause significant degradation to local water bodies, especially when it infiltrates groundwater or drinking water sources. Notably, marmettola production reported in the Single Environmental Declaration Model (MUD) has surged. While ornamental marble output has remained fairly constant, declared marmettola production jumped from 1,293 tons to over 27,000 tons between 2016 and 2018. This increase may reflect improved reporting and management practices, yet it also underscores the growing scale of environmental impacts. Effective waste management requires detailed assessments of material properties, including chemical composition, residual moisture (per EN 13755:2008), and particle size distribution. These factors are critical in evaluating potential reuse applications. Even minor variations can significantly alter the characteristics and usability of recycled products. For instance, $CaCO_3$ particles under 10 mm in diameter are unsuitable for some applications such as industrial blades, plasters, or glass. Uniformity in particle size is essential for ensuring consistent material performance. Contaminants like nickel, copper, cobalt, and chromium (Zichella et al., 2021) can further limit application options, making purification necessary before reuse (La Scalia et al., 2022). Unlike the Apricena stone basin in Puglia, where sludge is transported to landfills and allowed to dry naturally, the Apuo-Versilian district lacks a centralized drying protocol. Here, marmettola is often retained onsite or at processing facilities, maintaining moisture levels between 18% and 25%. Before it can be reused—for instance, in the production of cementitious or polymer-based materials—it must be adequately dried, adding an extra step to the processing chain. In conclusion, the Apuo-Versilian marble district is a complex ecosystem with significant economic importance and equally significant environmental challenges. To move toward a more sustainable and resilient future, the sector must prioritize resource efficiency, enforce yield regulations more rigorously, and innovate in waste reuse technologies. Balancing economic development with environmental protection will be essential in maintaining the district's global reputation while safeguarding its local ecological and social fabric.

CONCEPT: MODULAR SYSTEM AND DIGITAL FABRICATION FOR THE SUSTAINABLE REUSE OF STONE MATERIAL

Within the methodological framework outlined by the research, the concept of the modular system represents a possible design response for the sustainable and circular reuse of stone material. This proposal is based on the integration between emerging digital fabrication technologies and a systemic design vision, capable of combining technological innovation, the use of recycled material, and attention to the socio-territorial context. In particular, the design hypothesis considers the adoption of large-scale Additive Manufacturing techniques, such as 3D printing of mixtures composed of stone residues, to create modular components intended for technical or architectural application systems. However, the use of such technologies presents a series of design and technical challenges, which the research consciously addresses: the preservation of the material's physico-chemical properties, essential to ensure its stability and durability; the workability of the composite, meaning its ability to be extruded or printed through appropriate machinery; the management of processing temperatures and binding agents in the mixture formulation; the integration of form and function, considering not only the mechanical performance of the produced modules but also the achievable geometries.

In this scenario, the concept of customization in digital fabrication is not intended as mere aesthetic adaptation but as a key design lever, able to respond to specific territorial needs. Modular customization allows for the development of scalable solutions adaptable to different contexts, which can evolve from the prototyping phase to industrial production without losing the connection to the place's identity values. This perspective overcomes the limits of standardized design, embracing a model of distributed and situated design, where each module is configured as part of an adaptive and integrable system. The modular system, conceived in this way, serves as a tool for design simplification, capable of adapting and/or transforming through composable, efficient, and sustainable logics, fully respecting material and energy resources. In continuity with the principles expressed in other research directions—from morphological bio-inspiration to parametric design and the analysis of semiotic pollution—the modular system interprets design as a systemic and responsible practice, where technology is at the service of project logics and their meanings.

THE MODULAR SYSTEM: LIBRARY OF ELEMENTS AND CONFIGURATION STRATEGIES

In line with the principles of systemic design and with the goal of developing scalable, sustainable, and context-adaptable solutions, the design concept is based on the creation of a Modular System articulated into two main types of building elements: "block-based" and "panel-based". Both solutions rely on simple, repeatable geometries, designed to be assembled through joints and interlocking systems, thus creating flexible, reconfigurable structures capable of adapting to multiple application scenarios.

At the core of this approach is the intention to create a design toolbox of components — a library of physical modules that, through combinatorial logic, allows the generation of different configurations according to functional, spatial, and environmental needs. The system has been conceived for use in both indoor and outdoor contexts, with intended applications ranging from urban and domestic furnishings (seating, canopies, partitions, flooring) to technical and architectural surfaces (acoustic walls, refractory walls, retaining walls, ventilated facades, cladding surfaces). This application versatility is made possible by the definition of a shared design matrix, understood as an operational tool for framing and co-design among the various partners involved in the research. The matrix serves a dual purpose: on one hand, it guides the project development according to a modular and systemic logic; on the other, it allows the transparent and collaborative mapping of skills, materials, and processing hypotheses.

The structure of the design grid is organized according to well-defined thematic axes. Along the left vertical axis of the grid develops the guiding concept, identified as the "Modular System." This element traverses all the contents transversely, acting as a common thread and interpretative framework for reading the entire system. At the center of the grid are the stone materials, each represented in a dedicated table. The selected stones — Apricena Stone, Perlatino di Sicilia, Lava Stone, and Carrara Marble — are associated with their respective territorial GeoClusters, highlighting the connection with local extraction and production contexts. Each material corresponds to a section that collects the explored design solutions, organized horizontally according to the eight research units involved. Each table is vertically structured into two main thematic areas. The first, dedicated to “Walls / Surfaces”, includes applications such as cladding surfaces, ventilated facades, retaining walls, refractory walls, and acoustic solutions. The second, focused on “Indoor / Outdoor Furnishings”, includes elements such as flooring, seating, partitions, and canopies. Fig. 2

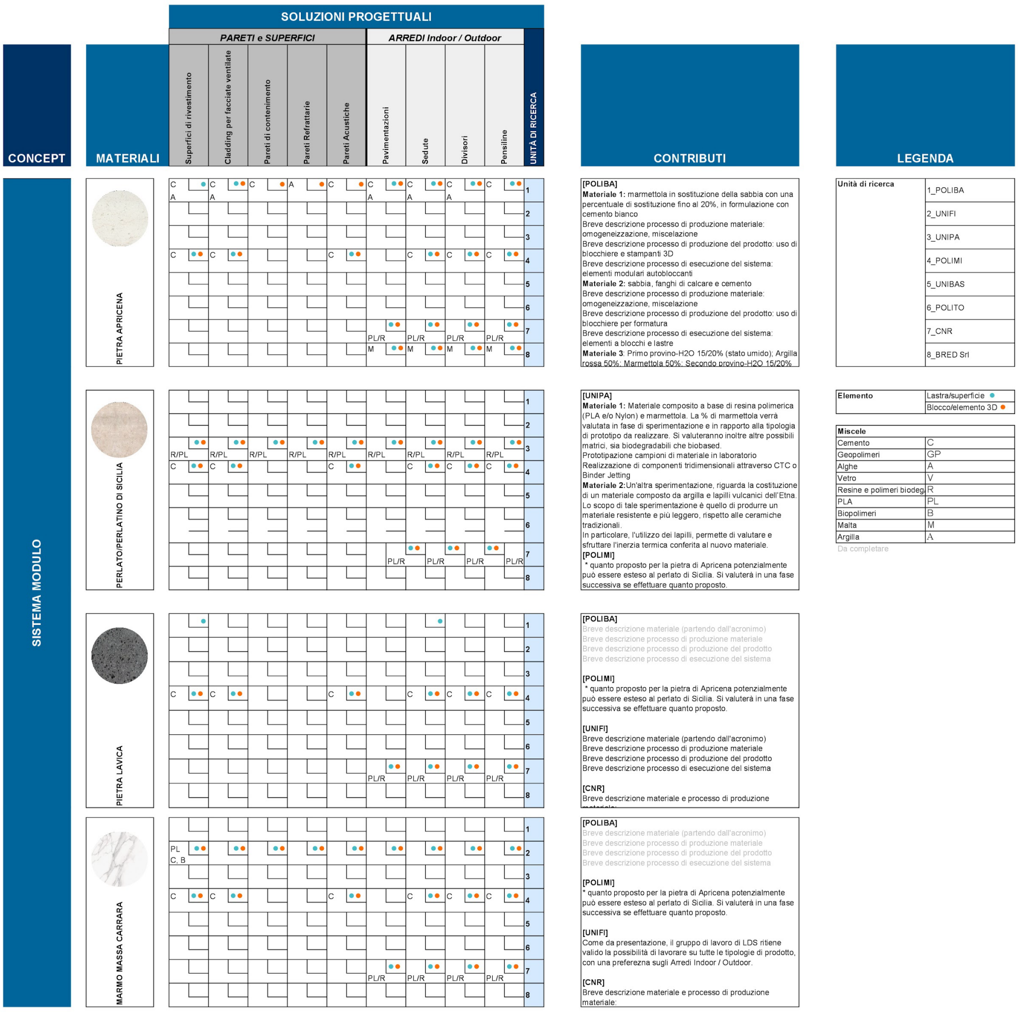

Fig. 2
Shared co-design matrix about design solutions.

For each partner, two colored circles indicate the element (block or panel) that is the focus of their research and experimentation activities. Next to these indicators, in the corresponding cells, the acronyms of the stone mixtures to be developed are listed, based on the technical characteristics required by the 3D printing technology and the functional needs of the module.
The hypothesized modular structure not only allows a coordinated and modular interpretation of the project but also constitutes an adaptive system, capable of evolving over time and responding to new needs, without compromising sustainability, simplicity, and coherence with the territorial contexts in which the system will be applied.

PROOF OF CONCEPT

In support of the previously described Modular System concept, an exploratory research phase was initiated to verify the design and technological feasibility of the approach, through the definition of morphological strategies inspired by natural models. In particular, attention was focused on the principle of tessellation, i.e., the periodic repetition of the same geometric shape — called a tessera — capable of completely covering a surface or volume without overlaps or gaps.

Inspired by recurring configurations in nature, this design solution is based on a highly efficient modular construction model, both functionally and structurally. The developed design hypothesis involves the transposition of the tessellation principle into the definition of modular elements, conceived as either “block” or “panel” types.

The design process is divided into two main phases: the first concerns the morphological optimization of the geometry through the use of generative and parametric algorithms, which allow defining shapes suitable for modularity and composability. The second phase involves the vertical extrusion of the obtained two-dimensional figure, transforming it into a three-dimensional module ready to be integrated into the composition of the entire architectural system. This process enables the exploration of new solutions for the construction and assembly of the modular system, as well as for designing the internal geometry of the individual module, optimizing its mechanical performance, lightness, and recyclability.

As extensively described, biomimicry processes and natural evolutionary strategies are a well-established and strongly integrated design reference in the STONE project. In nature, the tessellation principle manifests itself in various forms. For example, the turtle’s shell consists of a stratified composite: a porous bony core enclosed by dense outer layers and protected by a double-layer surface membrane (keratin and collagen), which simultaneously ensures structural strength and flexibility. Similarly, echinoids (e.g., sea urchins) feature a modular structure made of interlocking bony plates that allow the organism to absorb impacts and limit damage in case of breakage (Telford, 1985; Ellers et al., 1998). Fig. 3

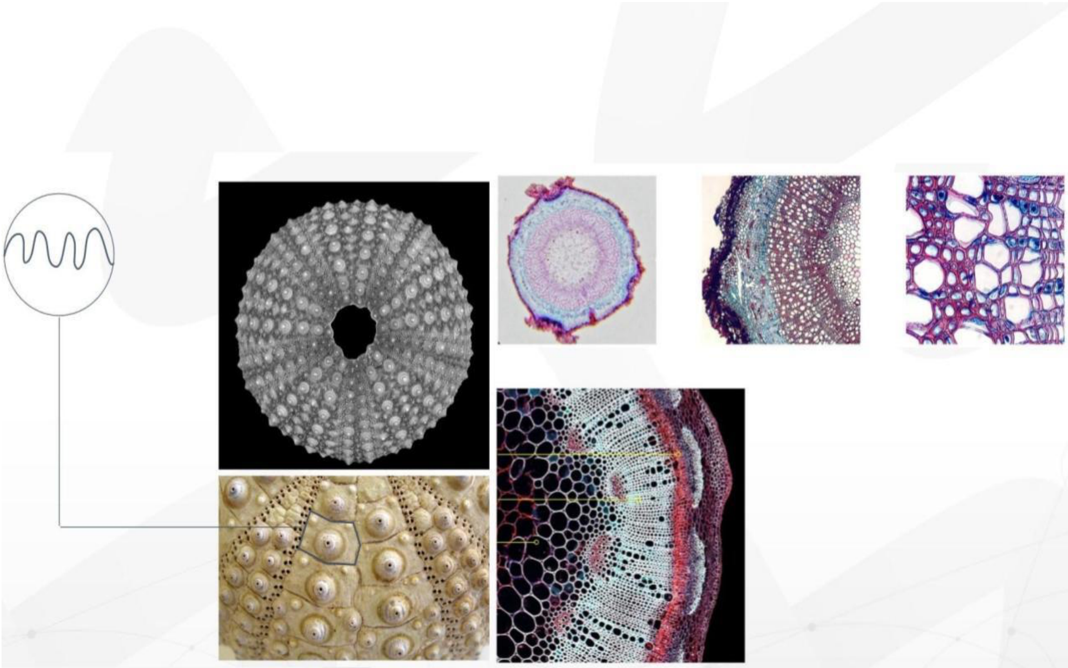

Fig. 3
Example of echinoid and Voronoi geometry. Tessellation.

Transferring these principles to architectural design, it is possible to formulate strategies that improve the resilience and sustainability of structures. For example, designing modular walls with replaceable plates — analogous to those of echinoids — can help reduce maintenance costs, extend the system's lifecycle, and minimize material waste. Within the STONE project context, the design applications of tessellation play a central role, contributing not only to formal and structural innovation but also to achieving sustainability goals. This design strategy stands out for its dual value. On one hand, it has a functional significance, as it enables the creation of lightweight, flexible, and easily repairable structures **Fig. 4**.

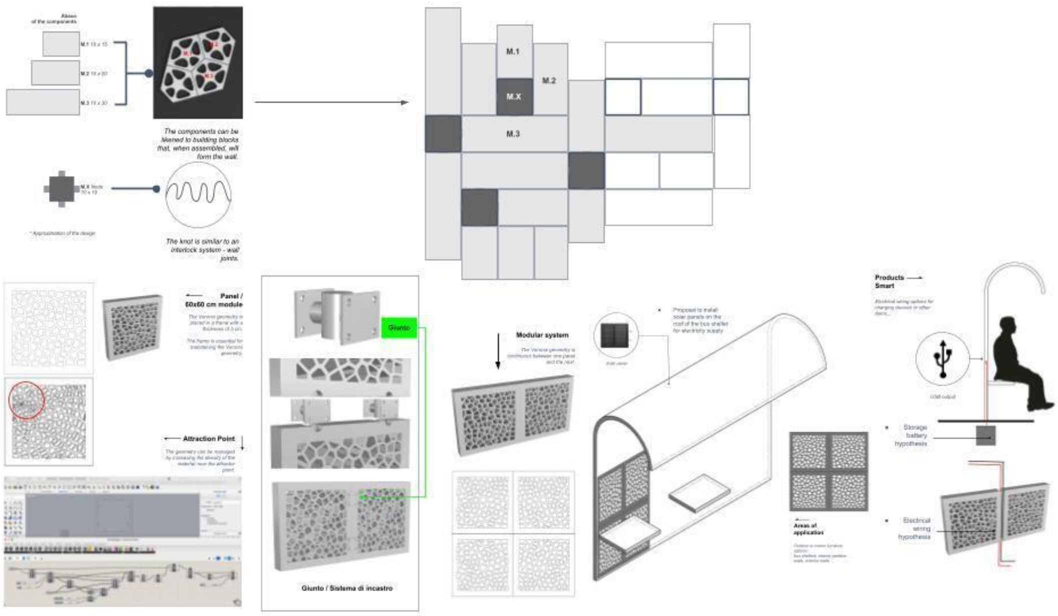

Fig. 4
Application of block and/or slab.

Thanks to the modular and composable nature of tessellation, such structures are adaptable to different installation contexts, offering versatile and dynamic solutions. On the other hand, a strong ethical and environmental component emerges. The use of tessellation promotes a more efficient use of material resources through the simplification of geometries, scalable modularity, and the possibility of selectively replacing damaged parts. This approach fully aligns with the principles of the circular economy, encouraging conscious design focused on durability and the product lifecycle. Fig. 5

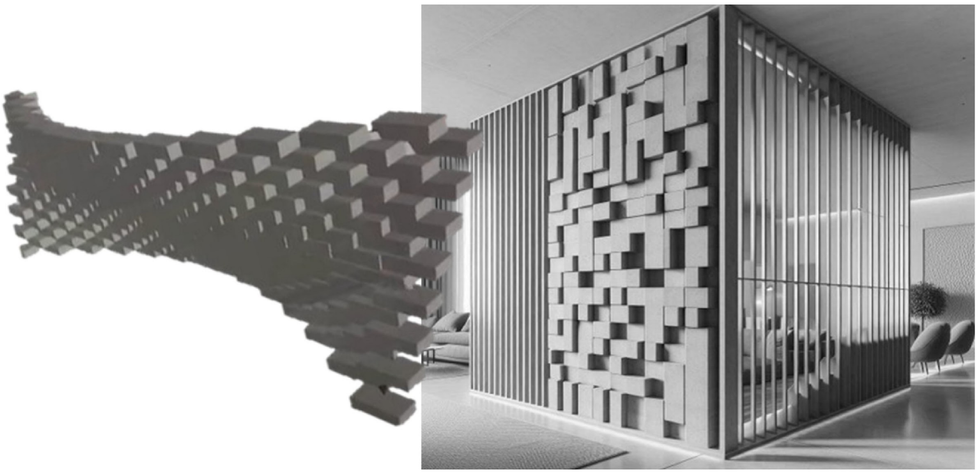

Fig. 5
Example of application.

This experimentation, deeply rooted in the paradigm of bio-inspired design and supported by the use of digital fabrication technologies, opens promising scenarios for the innovative reuse of stone material, translating the observation of nature into concrete solutions for the built environment.

THE STRATEGIC ROLE OF DIGITAL AND PARAMETRIC DESIGN

One of the most innovative and distinctive aspects of the STONE project lies in the advanced integration of parametric design with cutting-edge digital technologies. In a design context characterized by high complexity and multiple constraints, the use of generative design software enables the systematic and automated exploration of hundreds of morphological configurations, simultaneously optimizing the form according to structural, environmental, and functional criteria. The potential of this parametric approach lies in its ability to transform complex variables into opportunities for customization and performance. It is no longer a static selection among predefined solutions but a dynamic generation of adaptive forms capable of precisely responding to contextual needs and specific project requirements (Tedeschi, & Wirz, 2014). In this sense, digital design becomes a tool that synthesizes creative design, structural efficiency, and environmental sustainability. In parallel, the project has developed web platforms for participatory configuration, representing a significant advancement towards inclusive design models. These platforms allow designers and end users to interact directly with the creative process, customizing artifacts according to aesthetic, functional, and contextual criteria. This bottom-up approach not only enriches design quality but also helps reduce production waste through more targeted, on-demand manufacturing. From a production standpoint, the adoption of additive technologies such as 3D printing significantly increases process flexibility and efficiency. Compared to traditional methods based on rigid molds and standardized production lines, these digital techniques enable the creation of prototypes and small series with high precision, reduced lead times, and lower setup costs. This opens new prospects for a “digital-first” manufacturing model, capable of combining customization, speed, and sustainability.

CONCLUSION

The research conducted within the STONE project defines methodological frameworks for implementing systemic strategies aimed at building sustainable and resilient societies in territorial districts dedicated to the extraction and processing of stone. Concurrently, it provides technological guidelines for the development of innovative architectural products designed to meet specific performance requirements for indoor, outdoor, and temporary housing environments. This structured approach leads to the creation of eco-design products validated within a reference geocluster. Specifically, beyond the systemic approach adopted for the qualitative and quantitative analysis of the context in which circular economy strategies are activated, a design method oriented towards the ecological transition of the stone supply chain has been developed. To this end, a design methodology articulated along three main axes — morphological, technological, and conceptual — has resulted in the definition of a potential circular product solution. This solution, potentially integrable into a service system, is represented by a Proof of Concept based on modular elements “block-type” and “panel-type”, designed according to the principles of Design for Disassembly. Through the integration and dialogue between design and other scientific disciplines — from materials science to environmental engineering, from sociology to circular economy — the research has fostered fertile ground for the emergence of radically innovative technological solutions. These solutions not only address contemporary challenges but are also capable of anticipating and shaping sustainable future scenarios. This objective has been supported through the conception of a Modular System articulated in two main types of construction elements: “block” and “panel”. The composition of these elements was configured collaboratively among the various partners involved in the research, in terms of materials, morphology, and function, supported by the shared design matrix. This organization enables a cross-referenced and dynamic reading of the design contributions, relating materials, application fields, and approaches of the different research units within a unified and modular framework.

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