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Original Citation:

Made in Italy Eco-Designed Products from Stone Waste: The STONE Project / Monica Tonelli. - ELETTRONICO. - 3:(2024), pp. 295-306. (11th International Conference of Ar.Tec.).

Availability:

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(Article begins on next page)

12 August 2026

Metadata of the chapter that will be visualized in SpringerLink

Book Title	Proceedings of the 11th International Conference of Ar.Tec. (Scientific Society of Architectural Engineering)	
Series Title		
Chapter Title	Made in Italy Eco-Designed Products from Stone Waste: The STONE Project	
Copyright Year	2025	
Copyright HolderName	The Author(s), under exclusive license to Springer Nature Switzerland AG	
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Abstract	The Italian manufacturing sector is facing the challenge of transforming supply chains with a circular economy perspective, encompassing technological, organizational, and social aspects. In this regard, the scientific and technical communities are conducting research and experiments to enable the recycling of industrial waste, aiming to reduce the consumption of raw materials and environmental impacts. The Italian stone sector, which continues to hold the European primacy in the extraction and processing of natural stone, generates enormous quantities of waste such as “marmettola” (stone slurry/sludge) and “cocciame” (stone chips) each year. These are partially reused for certain low-value purposes, while the majority is disposed of in landfills, causing significant environmental impacts. In this context, the STONE project aims to propose innovative and eco-friendly materials and components that are Made in Italy, meeting the performance requirements for the design of indoor/outdoor living spaces and temporary housing solutions. Furthermore, a harmonized process for reusing waste from stone processing will be structured to manufacture eco-design products validated in the three reference geoclusters: Sicily, Tuscany and Apulia.

Keywords (separated by '-')	Stone waste - Sustainability - Ecodesign - PSS - Italian geoclusters

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Made in Italy Eco-Designed Products from Stone Waste: The STONE Project

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Keywords: Stone waste · Sustainability · Ecodesign · PSS · Italian geoclusters

1 Introduction

AQ1 Within global industrial supply chains, the production of construction and design components obtained from the processing of natural stone continues to play a strategic role in economic growth. In 2015 alone, a production of approximately 82.6 million tons

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R. Corrao et al. (Eds.): Colloqui.AT.e 2024, LNCE 612, pp. 1–12, 2024.
https://doi.org/10.1007/978-3-031-71867-0_20

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was recorded, with a waste extraction and processing percentage exceeding 70% of the gross quantity [1]. Within the European framework, Italy maintains its leadership as the fifth leading country in the stone sector, accounting for over 30% of the volumes. In this context, the increase in the production of worked and semi-finished stone leads to a rise in natural stone waste production, necessitating the identification of methods and tools for managing the environmental impact of this waste. This has resulted in efforts by academic and industrial research to minimize waste.

In literature, significant scientific interest is directed towards the recovery and recycling of stone slurry from extraction activities and processing plants [2–4]. This slurry is particularly explored as a fine aggregate for a wide range of composites, including both cementitious [5, 6] and polymer-based formulations, mainly with matrices based on sustainable materials, such as recycled materials, biodegradable and/or bio-derived polymers, or their blends. In this context, the STONE project (SusTainable ecOdesign reusiNg quarring wastE) aims to promote the sustainable use of "cocciame" (stone chips) and "marmettola" (stone slurry/sludge) from local extraction and manufacturing activities. These materials undergo analysis, taking into consideration the distinct territorial attributes of each region. This analytical approach facilitates the identification of geo-clusters, with a particular focus on the Sicilian basins adjacent to Mount Etna, where volcanic stone is extracted and processed. Additionally, attention is directed towards the fossiliferous limestone deposits in the proximity of Custonaci, the quarries in the Apulian region, including those in the Apricena district, and the Tuscanian marbles extracted from the Carrara district (Fig. 1).

The project is part of the Extended Partnership 11-PE MICS (Made in Italy Circular and Sustainable), involving universities, research centers, and businesses, funded by the Ministry of University and Research under the NextGenerationEU program. MICS is divided into eight thematic areas (Spokes), and the STONE Project is incorporated into "Spoke 2 - Eco-design strategies: from materials to product-service systems" (https://www.mics.tech/).

Currently, research lines on new design, production, consumption models, as well as end-of-life considerations for materials, products, production technologies, and processes transitioning towards greener and circular models, are expected to impact the three identified fundamental scenarios in the Italian industrial context of Made in Italy (Fashion, Furniture, and Automation). There is a future perspective to extend these impacts to other sectors such as construction.

Regarding Eco-design, in 2022, the European Community proposed a regulation on the eco-compatible design of sustainable products, structuring a framework for specification development, repealing Directive 2009/125/EC (the so-called Eco-design regulation). This proposal is part of a package of measures presented by the European Commission within the Circular Economy Action Plan of March 2020, aiming to drive the European economy towards a fully circular model. Specifically, new priority products and horizontal measures such as durability, recyclability, post-consumer recycled content, and related implementing provisions have been identified [7].

The community strategy of Integrated Product Policy sees Eco-design as a crucial factor because it promotes a preventive approach to product design to optimize environmental performance while preserving functional properties. The relative impact opens

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up new opportunities for manufacturing industries, consumers, and society [8]. The EEA (European Environment Agency) glossary defines Eco-design as "the integration of environmental aspects into the product development process, balancing ecological and economic needs. Eco-design considers environmental aspects in all stages of the product development process, seeking to create products with the least possible environmental impact throughout the product's entire life cycle" [9]. This entails the need to structure new business models involving all stakeholders in the process.

In this regard, product/service-systems have been considered strategic models in the development of sustainable societies through the provision of technological and systemic solutions. PSS is structured in a way that not only provides products but also services for improving usage and maintenance activities. These aspects will increase effectiveness and efficiency towards environmental benefits such as reduced material and energy consumption during production and use, extended producer responsibility for the use and end-of-life phase, the development of more durable products, high-quality end-of-life storage, reduced down-cycling, optimization of products based on their primary functions. The preliminary prerequisites are a much deeper understanding of product requirements, collection of end-of-life products to increase reuse, and easier updates to more eco-efficient technologies [10, 11].

This contribution aims to outline its methodological foundations (Sect. 2), the work structure (Sect. 3), and scientifically trace the potentials related to the investigated topic, highlighting also the perspectives of additional results from related research areas where the reuse of production waste can lead to the definition of circular and sustainable production chains at three levels: environmental, economic, and social.

Fig. 1. Geo-clusters' identification © 2023, Authors.

2 Research Objectives and Methodological Concepts

The open issues identified in the introductory framework will be addressed through the deployment of research activities of the STONE project. Apropos, the key elements of the problem are translated into specific research objectives.

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The implementation of Circular Management strategies aims to optimize processes, with the primary objective of mitigating environmental impacts arising from both waste disposal and the exploitation of raw materials at the geocluster level. For this purpose, an initial analysis of extraction and processing of natural stone in the three geoclusters is required, identifying resource flows and quantities in input (extracted and processed stone material, estimated energy consumption, emission estimates, estimated process water quantity, transportation) and output (solid waste such as "cocciame" and fluid waste such as slurry, which becomes powdery when dehydrated). The goal is to reshape waste reuse processes and assess the environmental impacts of potential products. Furtherly, the project will promote innovation in Made in Italy products, precisely developing high-quality eco-friendly products, reusing stone waste through bio mineralization processes, and components (e.g., objects, tiles, boards, and panels) for indoor/outdoor living spaces and temporary housing solutions. Starting from functional design, performance project characteristics based on industry regulations and the needs of manufacturers and end consumers are identified and studied. Moreover, chemical/physical and mineralogical characterization of stone waste is crucial to enumerate potential scenarios. Innovative solutions will address material and product challenges identified through systematic analysis of scientific and patent literature of cement-based and polymeric products.

As a consequent research objective, the project will boost the technological transition with digital methods (Additive Manufacturing). Digital methods, specifically additive manufacturing, will be experimented to produce modular, scalable, versatile components, with a focus on disassembly and reuse at the end of life.

Prototyping conceptual solutions will involve experimentation with 3D printing in addition to traditional moulding. The goal is to produce modular elements suitable for different scales of projects, including disassembled components for reutilization in various contexts. The overall aim is to achieve a transition towards advanced and sustainable production methods. These specific research objectives align with the overarching goal of the project, which is to contribute to sustainable and circular practices within the Italian manufacturing sector, particularly in the stone industry.

3 Project Actions

The STONE project aims to develop new solutions and tools that could shift stone extraction and production waste from landfills, improving the utilization of secondary raw materials in cutting-edge, high-quality Made in Italy industries. Therefore, beyond the environmental benefits of the waste-to-resource approach, the objectives are designed to be advantageous from various perspectives. The cultural dimension stands to gain from training initiatives facilitated by universities, focusing on transitioning towards circular and sustainable supply chains. These efforts, directed towards businesses, will leverage the expertise of researchers and innovation managers to promote awareness and capacity building.

Concurrently, consumers, another integral link in the chain, will be encouraged to adopt sustainable behaviours through proposed pathways, thus influencing the social landscape. The project aims to devise inclusive and effective strategies, harnessing digital technologies, for implementation within businesses.

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Moreover, the project endeavours to generate economic value by reuse of stone waste within circular supply chains, countering the disposal expenses presently borne by the stone extraction and processing industry. Notably, the identification of local geo-clusters will enhance the optimization of circular management, while digital technologies will streamline processes and enhance the scalability of solutions. The target entities are Small and Medium Enterprises (SMEs).

1. The expected cultural, social, and economic benefits will be ensured by the diversity and complementarity of the partners involved in the STONE project, including universities, research centers, university spin-offs, stone extraction/processing company consortia, manufacturers construction materials, elements and components.
2. The research development actions are divided as follows (Fig. 2):
3. State of the art on the reuse of products and by-products from stone processing, with the aim of identifying the scientific, technical, regulatory, and patent framework. Additionally, conduction of waste characterization tests and screening of operations in extraction and processing environments, differentiating for each geo-cluster the production phase generating the type of waste and its respective quantities. This will lead to the development of two inventories related to materials, components, products, material formulations, and systems and processes, technologies, and design tools.
4. Performance report of materials and products based on transformation scenarios in the perspective of a circular economy, considering mechanical, chemical, and physical characteristics of potential products derived from the use of stone waste material and monitored sustainability performance.
5. Design by function of Proof of Concepts for products, characterized by modularity and disassembly, aiming at configuring indoor and outdoor spaces, extending durability while minimizing the energy and environmental footprint. Additionally, digital manufacturing technologies will be identified based on data and procedures to enhance standardization and quality control. Prototype solutions for innovative products utilizing stone extraction and waste production will include 3D-printed design objects and tiles for indoor/outdoor use based on extrudable formulations; cement/resin based slabs and tiles for internal and external finishes through inert substitution/integration of powders; cement-based surfaces shaped to provide functional properties; use of sustainable and biodegradable polymers.
6. Screening and selection of indicators, used in Life Cycle Assessment (LCA), Life Cycle Costs (LCC), Product Lifecycle Management (PLM) analyses, in order to formulate a comprehensive impact assessment across multiple scales and domains within the life cycle analysis.
7. Experimentation of sustainability evaluation protocols during the life cycle of selected solutions. This is aimed at assessing the reliability, durability, and sustainability of the solutions through the application of previously selected indicators and impact assessment methods.
8. Validation of Proof of Concepts for design solutions and identification of relevant industrial scenarios for their application. Testbeds will be planned to evaluate properties and durability and to examine sustainability evaluation protocols. The validated Proof of Concept will be disseminated as a portfolio of advanced design.

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9. Definition of a PSS (Product/Service/System) as a harmonized framework for circular and sustainable production chains for each of the eco-friendly solutions. This involves establishing processes, technologies, and tools for differentiated application domains and for various geo-clusters. Specifically, the needs of different stakeholders in the supply chain (e.g., suppliers, customers, consumers) will be analysed, in order to provide guidelines about performance-based evaluation, recycling scenarios, and transformation requirements.
10. Design and execution of promotional and educational activities to achieve awareness of the circular management of natural stone.

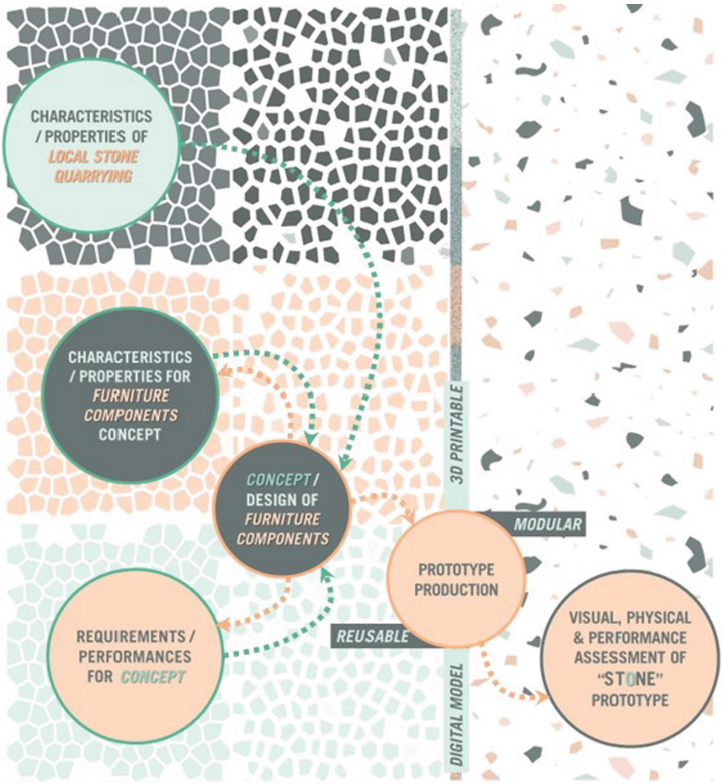

Fig. 2. Research framework of the STONE project © 2023, Authors

4 Specificity of the Transformation Basins of Stone Materials in the Three Italian Geo-Clusters

In this section, the analysis of the state of the art is reported, describing the regulatory framework underlying the regulation of extraction and processing activities of stones and marbles, initially at the national and European levels, down to the regional scale. The

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following section provides statistics and data related to quarries and volumes processed in different basins, as well as their mineralogical characteristics.

4.1 Regulatory Framework

At the national level, Italian extraction activities are still regulated by the Royal Decree of July 29, 1927, No. 1443, as no further regulation has been issued subsequently for the definition of unique criteria valid throughout the national territory, except for DPR 616/1977, which delegated administrative functions on quarry activities to the Regions.

At the European level, Directive 21/2006 imposed on Member States the adoption of appropriate measures regarding the management of waste derived from extraction activities, through the drafting of a waste management plan.

However, the legislation of different Italian regions on extraction activities retains heterogeneous characteristics, and there is a lack of adequate planning in many areas.

The waste produced by cutting and sawing stone is labelled with the CER code 010413, distinguishing them from those with code 010407 (waste containing hazardous substances, produced by chemical and physical treatments of non-metallic minerals, marked as hazardous) [12, 13]. The size of marble processing waste depends on the type of cutting and processing performed, as well as the nature and initial size of the block. Specifically, there are three types of waste: debris, slurry/sludge, and dust, differing in particle size and that can be reused in different ways.

Official statistics [14] report that in the period between January and August 2022, total Made in Italy exports of marble, natural stones, travertine, and granite increased by 14.3% compared to the same period of the previous year, reaching 1,304 million euros. The main contribution to sales comes from materials and semi-finished products, which, in addition to being the highest value-added products, represent over 3/4 of the value of Italian stone exports. However, this positive trend is correlated with the increasing production of related waste and, consequently, its environmental impact.

The by-products of the extraction quarry are produced during crushing and washing operations to facilitate the transport of the products thus obtained. These wastes represent significant sources of environmental criticalities; in fact, the sludge that spreads in rivers and streams alters their normal conditions, creating environments incompatible with the flora and fauna of the territory, not to mention the hydrogeological risk associated with the cementing of watercourses [15].

In addition to the environmental impacts, a considerable economic impact is recorded. The used landfills, including exhausted quarries used as deposits, are reaching saturation, generating significant disposal costs for miners, amounting to 20–50 euros per ton. Regarding the global market for calcium carbonate, its valuation in 2019 was $43.89 billion, with an expected annual growth rate of 2.8% from 2020 to 2027.

4.2 Analysis of Involved Geo-Clusters: Sicily, Tuscany and Apulia

As reported in the latest Cave Sicily 2021 Report by Legambiente, Sicily currently has 442 authorized quarries and 245 abandoned ones. With most of quarries extracting limestone and gypsum (198), followed by ornamental stones (81), basalt, tuff, and volcanic

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rocks (73), sand and gravel (43), and clay (27), Sicily ranks at the top in Italy in terms of the number of extraction sites, followed by Veneto, Apulia, Lombardy, Piedmont, and Sardinia. There are 140 municipalities with at least one authorized quarry in their territory, accounting for 36.1% of Sicilian municipalities. Areas with a higher concentration of extraction sites are in Custonaci, with 38 quarries, Castellammare del Golfo and Belpasso, both with 16 sites, Scicli, with 11, and Caltanissetta, with 10. Regarding the extraction of precious marbles, especially Perlato di Sicilia, Custonaci is the third extraction basin in Italy after Verona and Carrara, with an extraction capacity of 250 thousand tons per year, employing around four thousand workers when considering the entire industry. As for the extraction of basalt and lava stone, the productive district of Pietra dell'Etna, covering multiple provinces, includes companies mainly located in the provinces of Catania, Ragusa, and Siracusa. However, the Cave Sicily 2021 Report highlights the strong influence of unauthorized quarries on the lava stone sector. Approximately 20% of the marketed volcanic material in recent years reportedly did not originate from authorized quarries, [16]. Despite the mentioned data, there has been a challenge in acquiring and processing data on extractions and processing waste over the years. Extraction companies should voluntarily provide this data to the Department of Energy and Public Utility Services of the Sicilian Region. Especially concerning processing waste, this could be due to the economic burden on companies to transport waste material to mills for potential reuse, as well as the lack of clarity and transparency regarding the path of demolition and reconstruction waste, and the absence of incentives for more virtuous behaviours in terms of environmental conservation and circularity. This represents the most urgent issue to address in Sicily since, [17], 70% of the gross extracted product consists of processing waste. From the analysis of data provided by the Department of Energy and Public Utility Services, several gaps have been identified, particularly concerning the quantity of extracted material rather than the partial quantities of unusable blocks (considered processing waste) and stone chips. This currently hinders a precise estimation of the quantity of waste material produced by Sicilian extraction companies. Nevertheless, recent initiatives have been started in order to enhance collaboration among different stakeholders in order to find solutions to these issues, as industry representatives and professionals. They have established a protocol to improve the knowledge and protection of the Trapani stone sector, reconciling environmental needs with productive ones.

Regarding the Tuscany Geo-Cluster, stone materials (such as marble and granite, especially when processed) represent 20% of exports from Massa-Carrara (2022), amounting to a value of 417 million euros (+17.9% compared to 2021). Significant results have also been achieved concerning the raw stone material, valued at 202 million euros (€) [18]. Considering these data, it is crucial to also consider the associated waste production, considering potential environmental issues for the local flora and fauna. For example, some studies estimate that, considering a marble block's weight of 24.3 tons, 11.7 tons of sludge are expected using the frame saw, 11.9 using the diamond wire, and 13.5 using the diamond blade [19]. In 2014–2015, data report the presence of 104 quarries, 82 in Carrara district (79%) and 17 in Massa (16%). There are five main marble basins: Colonnata, Pescina, Miseglia, Torano and Boccanaglia. The province of Massa Carrara shows a level of extraction exceeding 72% of the entire Tuscan regional sector. It

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is important to specify that to classify a quarry as a "quarry for materials for ornamental the extraction site", it should obtain at least 25% of cutting materials or produce blocks. In 2024, the number of marble quarries in the district is decreased to 74 [20]. It is also relevant to note that that Carrara marble is the Tuscan product that travels the greatest number of kilometers logistically than other products of the region. The amounts of waste from the production lines is not negligible. In the three years 2012–2015, it was reported a production of 77303 tons while in 2018 is reported a total production of debris of 2247886 tons in the Tuscanian Geo-Cluster [21, 22].

In the Apulia Geo-Cluster, the Apulia Stone District was founded in 2007 [23]. It was officially acknowledged by the regional government on July 19, 2010, with the primary objective of fostering the growth of the stone sector. This initiative aimed to address regulatory uncertainties, enhance companies' investment capabilities, and facilitate the adoption of new technologies within the industry. However, this initiative was discontinued in the following two years. Since 2007, the development program for the district documented that the Apulia stone sector was lagging in implementing technologically advanced, safe, and sustainable supply chains, despite high volumes of raw material production and commercialization. Additionally, the absence of specialized excellence centers and structures in stone processing and transformation technologies was noted. In recent years, the export of stone material has also grown, especially to the United Arab Emirates (Apricena stone was exported by Stilmarmi in 2019 for a total of 80,000 euros). Also in the Apulia basin, the volume of stone waste is significant, prompting PRAE PUGLIA (Regional Plan for Extractive Activities) to support projects for recovering and utilizing waste from extraction activities (stone chips) and processing (marble dust). In 2019, the Apulia Region promoted the sustainable development of extractive industry, ensuring the recovery of quarry sites and containing soil consumption and non-renewable resource extraction, encouraging the reuse, recycling, and recovery of waste materials from extractive activities, favouring the expansion of current sites over the opening of new extraction sites [24]. Among the entire Apulian basin, the Apricena one will be analysed, as the one with quarries still active. The characterization of waste products is strongly linked to the varieties cultivated in the Apricena basin, which are Fiorito, Biancone, and Serpeggiante. Fiorito consists of fine and very fine-grained beige-brown limestone with streaks, calcite veins, and/or stylolite. When Fiorito has a low concentration of bioclasts, it is classified as Biancone. Macchiettato has high concentrations of fossil remains and spatic calcite. Filetto rosso has frequent red stylolites. Biancone is fine to medium-grained limestone, whitish or beige-brown, with stylolites. The intermediate part of the succession consists of finely laminated beige-brown limestone. Serpeggiante has a greater thickness than the previous ones, with a higher sterile thickness and a concentration of lithotypes with distinct lamination highlighted by chromatic variations. The processes of transforming Apulia stone can be summarized in excavation, producing "benches" worked in the quarry to obtain "blocks", "semi-blocks" or "formless" pieces. After undergoing the pulverization process, the waste is directed towards one of two paths: disposal in landfills or distribution for utilization in various industrial processes, such as pharmaceuticals, chemicals, and more. The waste from processing is also used

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for environmental restoration activities in disused quarries, which have become landfills, faithfully reproducing the pre-existing conditions before productive activity (e.g., S. Sabino landfill managed by the Conpietra consortium).

5 Application Potential and Project Impact

The objectives and actions will lead to the design of products and services that minimize waste, identified as 'Design of PSS solutions - 0 waste'. These products, although tied to the material specificity and organizational structure of the extraction and processing activities in the three geoclusters, will feature components of high performance and environmental quality. They can be applied as design elements for indoor/outdoor living spaces and temporary housing solutions. Furthermore, the definition of the harmonized framework of processes, technologies, and tools for the sustainable use of stone extraction and production waste among the stakeholders in the supply chain (identified as Design Strategies). As clarified in the initial context framework, the project aligns with European initiatives aimed at bringing tangible impacts to small and medium enterprises by supporting them with knowledge and methods during the transition to a circular economy. Moreover, in terms of management and environmental impact analysis, the project will result in the development of novel assessment methods to ensure adherence to circular economy principles. This includes the utilization of standard and experimental Life Cycle Assessment (LCA) approaches, exploration of innovative resource allocation methods ranging from the 0–100 approach to defining allocation factors in the Product Environmental Footprint approach. This aligns with the cutting-edge objectives established by the technical committees of the European Union, particularly in pilot projects focusing on the repurposing of industrial, agricultural, textile, and food waste.

6 Conclusion

The STONE project achieved initial results concerning the analysis of the state of the art in scientific literature and patents related to materials and products that reuse stone waste. This involves identifying mixtures and production processes, as well as the chemical/physical characteristics and mechanical properties of these materials. Moreover, in-depth studies conducted by researchers in each geocluster allowed the characterization of stone waste through laboratory tests and the modelling of current stone processing and waste production processes. Additionally, some performance indicators for products relevant to the functional design of sustainable design components have been identified.

Acknowledgements. This study was carried out within the MICS (Made in Italy – Circular and Sustainable) Extended Partnership and received funding from the European Union Next-Generation EU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.3 – D.D. 1551.11–10-2022, PE00000004). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

The authors are thankful to: Scioti A, Bruno S, Baccaro A (POLIBA), Speroni A, Pittau F, Bianchini M, Standoli C, Bolzan P (POLIMI), Famoso M, Catania AM, Del Puglia S (UNIPA), Marini P (POLITO), Marseglia M, Pontillo G, Bonini M, Alessio T (UNIFI), Arrighetti L, Ricci L, De Monte C (CNR-IPCF Pisa).

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Chapter 20

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