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DuSTcube: A Stereotomic 3D-Printed Housing Unit Meant for Mediterranean Areas

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This study investigates how stereotomic rules and 3D printing technology can be combined to develop a sustainable housing system for post-disaster reconstruction in Mediterranean contexts. The study adopts a design-based research methodology consisting of literature analysis, extraction of vernacular design principles, stereotomic geometric development, digital fabrication strategies and critical evaluation of the resulting prototype feeding into the design of a minimal housing module. The module measures 25 square meters and it comprehends all the essential services of a house, while remaining fully modular. The unit is designed to be composed of stereotomic ashlars made of 3D-printed stone, which can be assembled without the use of centrings thanks to the conical profile of the internal vaults. The adoption of 3D printing allows the blocks to be customised in terms of shape and porosity, without waste, enabling the various components to be optimised according to their static behaviour, weight or to insulation requirements. Moreover, the construction process can be kept environmentally sustainable by using recycled material, such as waste stone powder or debris from the demolition of existing buildings. The paper proposes a research framework that combines stereotomic design, additive manufacturing and Mediterranean architectural knowledge, opening new directions for sustainable post-disaster reconstruction.

Introduction

Nowadays, the AEC (Architecture, Engineering and Construction) field has been characterised by a large amount of research focused on sustainability. As a matter of fact, it is estimated that 37% of the global emissions come from the construction industry[1] and that the most used materials, such as concrete, steel and aluminium, have a great carbon footprint.[2]

According to the objectives of the European Green Deal,[3] it is important to consider the necessity to change our way of building, using green materials, trying to recycle industrial waste as the main resource and finding new strategies to keep the built structures sustainable in the long term.

The focus of this paper is the Mediterranean basin, where post-disaster reconstruction poses not only environmental but also social, cultural and technological challenges. Although recent advances in sustainable construction and digital fabrication have opened new possibilities for housing design, limited

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1. European Commission, *Building and construction.*
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3. European Commission, *The European Green Deal.*

attention has been devoted to integrating Mediterranean vernacular principles, stereotomic construction and additive manufacturing within a unified architectural strategy. Against this background, a new paradigm of a stereotomic Mediterranean House, named DuSTcube, is proposed.

The name DuSTcube explains the essence of the project, which appears as a cubic volume with arched openings and which has been thought to be fabricated using the 3D printing of dust (stone powder, desert sand, etc.).

In the Mediterranean area there are several examples of places in need of reconstruction operations. In Syria, for example, a ten-year conflict has caused the destruction of cities and heritage, and the population has been forced to move from their homes to new places. This phenomenon has caused social pressure and tension that local governments were unable to mitigate also because of limited financial possibilities.[4]

Italy, on the contrary, has witnessed some natural disasters due to climate change: floodings and landslides are dangerously growing, and so is the urge not only to contain their effects but also to find fast and cheap solutions for those people whose houses are damaged or even destroyed. The flood that hit Emilia Romagna in May 2023 caused extensive damage to infrastructure, buildings and essential services, with significant social and economic impacts.[5]

Moreover, the latest years were characterized by an increasing of migratory fluxes. For example, 123,000 immigrants arrived in Europe in 2021, and this phenomenon has been encouraged by the conflict between Russia and Ukraine, from which more than 1 million people escaped looking for shelter,[6] highlighting the need for innovative housing systems that combine rapid deployment, sustainability, efficiency and adaption to the cultural and climatic characteristics of the place they are meant to be built.

In a world afflicted by conflicts and disasters, DuSTcube is a "vision" for long-term reconstruction in the Mediterranean area. It represents an architectural synthesis of innovation, sustainability and cultural heritage that helps reaffirm the role of the Mediterranean identity in shaping the future of resilient and responsible design.

Literature Review

The optimal development of this project has required a focus on a series of themes such as current architectural solutions for shelters and emergency dwellings, the Mediterranean vernacular architecture, and the stereotomic discipline. The literature review has helped face the design phase with more awareness.

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4. UN-Habitat, *Restoration of cultural heritage and urban identity in Syria.* Urban Recovery Framework, 2021.

5. L. Cremonini, P. Randi, M. Fazzini, M. Nardin, F. Rossi, and T. Georgiadis, "Causes and Impacts of Flood Events in Emilia-Romagna (Italy) in May 2023," *Land* 13, no. 11 (2024).

6. R. Bruno, P. Bevilacqua, A. Rollo, F. Barreca and N. Arcuri, "A Novel Bio-Architectural Temporary Housing Designed for the Mediterranean Area: Theoretical and Experimental Analysis," *Energies* 15, no. 9 (2022).

Building in Post-Disaster Contexts

In post-disaster contexts, it is necessary to categorise the different types of dwelling solutions: they can be distinguished into emergency shelters, transitional shelters and transitional housing.

Emergency shelters are usually meant to immediately host the victims of a disaster and to be used for a very short period after the disaster, sometimes only a few hours.

Temporary shelters are meant to continue to provide essential goods and to host people for a relatively short time. Emergency and temporary sheltering can be distinguished especially for behaviour matters: for example, in temporary sheltering cases it is important to understand where and how the victims will be fed, while in emergency sheltering cases this does not happen because the stay will be too short. Temporary housing is meant to host people for a period that can vary between six months and a few years and, for this reason, it consists of more "robust" structures that allow people to run all the activities of everyday life.[7,8]

Currently, existing temporary housing solutions are often inadequate because they are conceived by designers or technicians who are not familiar with the context, and who, consequently, neglect the real needs and the identity of the population.[9] Moreover, they often are not sustainable because of the use of materials with a high embodied carbon, as concrete and steel, and because of a lack of attention towards the recyclability and the reuse of the components.[10]

For example, the Gümüspinar Temporary Settlement realised after the 1999 earthquake in Turkey, has been built using mainly prefabricated components made of a blend of cement, wood shaving chipboard and zinc-aluminium. This solution makes this housing system not environmentally friendly, due especially to the lack of awareness about the theme of sustainability in 1999. Moreover, the housing solution did not consider the local identity and needs.[11]

A more virtuous example is represented by the "Superadobe" developed by Nader Khalili in 1984 (Figure 1). It consists of a domed structure realised by piling up layers of bags full of raw earth and dirt, which helps obtain thick walls able to resist bad weather conditions and natural calamities (e.g., floods or earthquakes). The Superadobe is a very sustainable system since it is realised with local materials and can be assembled by the population itself after a training period.[12] Despite the

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7. E. L. Quarantelli, "Patterns of sheltering and housing in US disasters," *Disaster Prevention and Management* 4, no. 3 (1995): 43-53.

8. R. Lines, J. P. Faure Walker, and R. Yore, "Progression through emergency and temporary shelter, transitional housing and permanent housing: A longitudinal case study from the 2018 Lombok earthquake, Indonesia," *International Journal of Disaster Risk Reduction* (2022): 75.

9. D. Félix, A. Feio, and J. M. Branco, "Guidelines to Improve Sustainability and Cultural Integration of Temporary Housing Units," in *Proceedings of the 6th International i-Rec Conference. Sustainable Post-Disaster Reconstruction: From Recovery to Risk Reduction* (Ascona, Switzerland, 26-30 May 2013).

10. G. Montalbano, and G. Santi, "Sustainability of Temporary Housing in Post-Disaster Scenarios: A Requirement-Based Design Strategy," *Buildings* 13, no. 12 (2023).

11. Ibid.

12. A. H. Abulnour, "The post-disaster temporary dwelling: Fundamentals of provision, design and construction," *HBRC Journal* 10 (2014): 10-24.

sustainability and the easy construction process, the assembly of a Superadobe requires a considerable number of people and physical strength to be completed.[13] Moreover, this kind of solution puts some limitations from the geometric point of view.

Figure 1. *A Superadobe Structure Built in Djibouti (Africa) by Andrew Caya*
Source: Photos by Andrew Caya, taken from www.dvidshub.net/image/591295/new-eco-dome-signals-changes-local-village.

Nowadays large-scale 3D printing is becoming an alternative for the realisation of housing modules. A good example is represented by the houses built in Nacajuca (Mexico) by the company ICON together with the non-profit organisation New Story. These houses, meant for people in extreme poverty conditions, are composed of 3D printed monolithic walls and a wooden roof. The houses have been designed with the feedback of the locals in order to meet their needs; moreover, since Nacajuca is in a seismic zone, the structures have been conceived according to safety requirements.[14, 15] The material used for the 3D printed part was a special concrete developed by the American company, and this goes against the principle of using local and sustainable materials. Moreover, this kind of large-scale additive manufacturing, which works through the extrusion of the fluid mortar, requires very heavy machinery, which implies a big initial financial investment.

Overall, the reviewed literature highlights a persistent trade-off between construction speed, environmental sustainability and adaptation to local cultural contexts. While earth-based systems offer low environmental impact but require labour-intensive construction processes, large-scale concrete printing enables rapid fabrication at the expense of material sustainability and transportability. These limitations suggest the need for

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13. R. Kamal, and M. S. Rahman, "A study on feasibility of super adobe technology –an energy efficient building system using natural resources in Bangladesh," in *IOP Conference Series: Earth and Environmental Science* (2018): 143.

14. B. Baguess, *ICON + New Story + ECHALE Unveil First Homes in 3D-Printed Community* (ICON Website, 2019).

15. M. Bazli, H. Ashrafi, A. Rajabipour, and C. Kutay, "3D printing for remote housing: Benefits and challenges," *Automation in Construction* (2023): 148.

alternative construction strategies capable of combining resource efficiency, digital customisation and stronger integration with local architectural traditions.

The Vernacular Architecture as a Source of Inspiration

As previously said, the main purpose of this project is to create a model of architecture meant for post-disaster housing with specific attention to the architectural identity of the Mediterranean basin and to sustainability.

Mediterranean vernacular architecture has been built mainly with stone, and it is characterised by massive structures often covered with vaults or pseudo-vaults, with a few openings which sometimes have an arched profile (Figure 2).

Figure 2. *Some Mediterranean Vernacular Structures: a) Trulli in Cisternino (Apulia, Italy); b) The Old City of Mardin (Turkey); c) A Traditional Dammuso from Pantelleria (Sicily, Italy)*
Source: a) photo by José Jovena; b) photo by Osman Karagöz; c) iStock.

These historical structures are also known to have a good performance from a sustainability point of view.

A study conducted by the University of Miho, focused on the city of Nablus in Palestine, has shown that the old city centre has a better performance than the new one. As a matter of fact, some graphs show that the energy requirement for heating and cooling artificial systems is lower for traditional buildings than for new ones. Moreover, a lower carbon footprint has been estimated for the traditional construction materials considered, among which stone is mentioned, rather than for new ones.[16]

Vernacular Mediterranean architecture often presents a series of passive cooling strategies favoured by the material used and by the formal configuration. First of all, the high thermal inertia of stone guarantees a slow heat exchange between the interior and the exterior (Figure 3a).

Stack effect is another fundamental strategy that guarantees passive cooling. In Apulian *trulli* warm air can flow out through cracks in the pseudo-vault, thus

16. F. Al Tawayha, L. Braganca, and R. Mateus, "Contribution of the Vernacular Architecture to the Sustainability: A Comparative Study between the Contemporary Areas and the Old Quarter of a Mediterranean City," *Sustainability* 11, no. 3 (2019): 896.

sucking up fresh air. Cooling was also favoured by the presence of a water tank underneath the structure[17] (Figure 3b). The same effect is obtained in vaults that present an opening on the ceiling, like the *Kolah farangi* in the Iranian architectural tradition. A *Kolah farangi* is a hole on the vaulted ceiling meant to work both as a natural light catcher and as a means for natural ventilation[18] (Figure 3c).

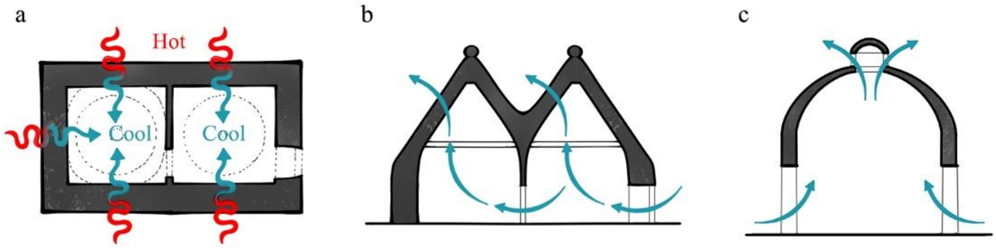

Figure 3. *Schemes of Some Passive Cooling Strategies in Vernacular Mediterranean Architecture: a) The Effects of High Thermal Inertia of Stone in a Trullo; b) Stack Effect in a Trullo; c) Stack Effect in an Iranian Kolah Farangi*
Source: schemes by the authors.

Sustainability is also strictly linked to the theme of water management, especially in the Mediterranean area, where water scarcity is increasing because of climate change. This is happening especially in the Southern and Eastern Mediterranean countries.[19] Sometimes systems for water collection and reuse have been developed since antiquity: a good example is the complex system of cisterns realised in the city of Matera, where water is not abundant[20] (Figure 4).

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17. M. Stigliano, "Towards a sustainable design project," in *Stereotomy. Stone architecture and new research* (ed.) G. Fallacara (Paris: Presses des Ponts, 2016), 188-209.

18. M. M. Zarandi, "Natural ventilation as a solution towards sustainability in architecture," in *Proceedings of the International Workshop on Energy Performance and Environmental Quality of Buildings* (Milos, Greece, 6-7 July 2006).

19. E. Ferragina, "The water issue in the Mediterranean," in *Environmental and Sustainable Development in the Mediterranean* (eds.) M. Scoullos and E. Ferragina (Barcelona: European Institute of the Mediterranean, 2010), 53-79.

20. M. C. Grano, "Palombari, cisterne e pozzi per l'approvvigionamento idrico nei Sassi di Matera (Basilicata)," *Il Capitale Culturale. Studies on the Value of Cultural Heritage* 21 (2020): 377-389.

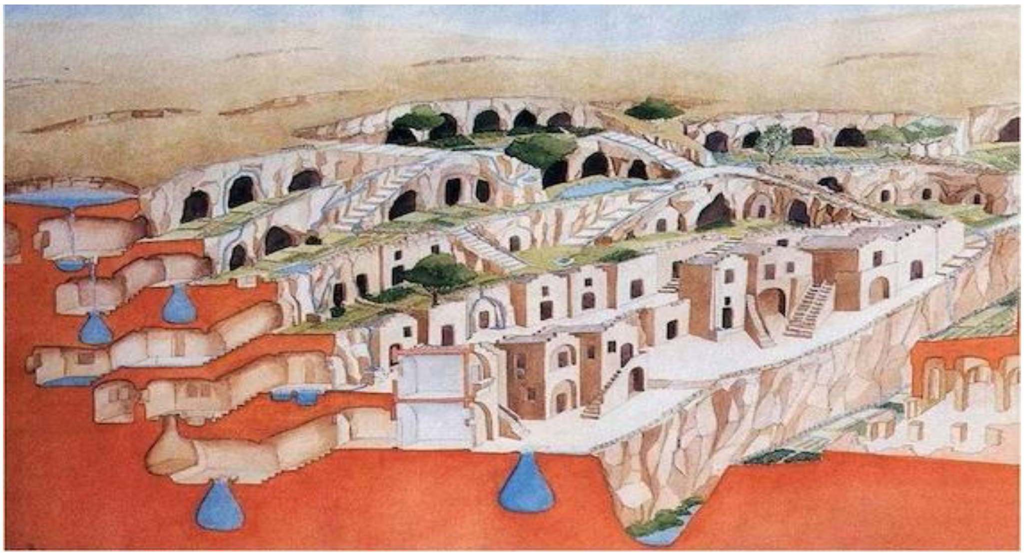

Figure 4. *A Scheme of the Water Collection in the Sassi of Matera*
Source: Drawing by Debora Giorgi.

These examples demonstrate that Mediterranean vernacular architecture should not be regarded merely as a historical reference, but as a repository of environmental design principles that can inform contemporary construction systems. Rather than reproducing traditional forms, the present research investigates how these passive strategies can be reinterpreted through digital design and fabrication technologies.

Stereotomy: A Construction Discipline Born in the Mediterranean Area

In the design process of DuSTcube, the principles of stereotomy have been considered and applied. Stereotomy is an ancient discipline also known as "the art of cutting solids", which was used in the past to design and realise masonry vaults. This discipline was based on the application of the rules of projective geometry to design vaulted spaces discretised optimally, considering both static and aesthetic matters.[21]

Stereotomic systems are historically associated with the use of stone and are meant to produce mainly compressive stresses and to work even without mortar or reinforcements. Architecture must respect three invariants to be considered stereotomic:

1. Prefigurative invariant: the overall geometry of the vaulted space must be determined, and its configuration must be clear.
2. Technical-geometric invariant: every single constructive element (ashlar) must be geometrically defined, and it must be represented in order to be correctly produced.
3. Static invariant: the equilibrium of the structure must be guaranteed.[22]

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21. G. Fallacara, and R. Gadaleta, "Stereotomy: Architecture and Mathematics," in *Handbook of the Mathematics of the Arts and Sciences* (ed.) B. Sriraman (Cham: Springer, 2019).

22. G. Fallacara, *Towards a stereotomic design. Notions of stereotomy, digital stereotomy and topological transformations: reasoning about the construction of the form* (Rome: ARACNE Editrice).

Many Mediterranean vernacular architectures, as the ones discussed in the previous paragraph, present vaulted spaces, but not all of them can be considered stereotomic. For example, a *trullo* is not a stereotomic structure, since its roof is built using juxtaposed irregular rocks, which create a so-called pseudo-vault instead of a vault (the technical-geometric invariant and the static invariant are not respected). Also vaults made of bricks cannot be considered stereotomic because they are composed of standardised elements instead of ashlars optimised specifically for the structure (the technical-geometric invariant is not respected).

Even if stereotomy has reached its theoretical and practical peak in France in the 16th-17th century, there are examples of stereotomic architectures since the Hellenistic period in a wide geographical area whose centre is the Mediterranean Basin.[23] Stereotomic vaults are part of the Mamluk architectural heritage (various of them, for example, are placed in the Cairo Fatimid Walls[24]) and are also present in many historical buildings of southern Italy, Spain, etc.

Therefore, stereotomy can be considered part of the Mediterranean identity, and designing a housing module through an innovation of this discipline would not only take into account sustainability and ecological matters, but also cultural ones.

Using stereotomy can help obtain very effective structures and reduce the need for metal reinforcements – since stereotomic structures work mainly under compression loads – and this can help keep the construction process greener. However, it is a very complex discipline that requires a specific know-how, and nowadays it is explored mainly in universities research institutes to obtain experimental pavilions and temporary structures designed using form-finding algorithms, parametric modelling software and realised using digital fabrication technologies.

Some examples are the *Armadillo Vault*, realised by the Block Research Group of the ETH Zürich for the International Architecture Exhibition organised by La Biennale di Venezia in 2016[25] (Figure 5a), *Stone Matters* realised by AAU Anastas Architects in Jericho in 2017[26, 27] (Figure 5b), the *Hypar Vault* (Figure 5c) and the *Flux Vault* (Figure 5d), both realised by Giuseppe Fallacara with the New Fundamentals Research Group in 2017.[28] There are also some recent examples of 3D printed stereotomic shells, such as the *Striatus Bridge*, realised by Zaha Hadid

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23. S. Galletti, "Stereotomy and the Mediterranean: Notes Toward an Architectural History," *Mediterranean International Journal on the Transfer of Knowledge* 2 (2017): 73-120.

24. M. Salcedo-Galera, and R. Garcia-Bano, "Stonecutting and Early Stereotomy in the Fatimid Walls of Cairo," *Nexus Network Journal* 24 (2022): 657-672.

25. M. Rippmann, T. Van Mele, M. Popescu, E. Augustynowicz, T. Echenaguci, C. Barentin, et al., "The Armadillo Vault. Computational Design and Digital Fabrication of a Freeform Stone Shell," in *Proceedings of the Conference Advances in Architectural Geometry 2016* (Zurich, Switzerland, 9-13 September 2016) (eds.) S. Adriaenssens, F. Gramazio, M. Kohler, A. Menges, and M. Pauly, 344-363.

26. Y. Anastas, O. Baverel, and M. Brocato, "Design-to-construction workflow for free-form Abeille stone structures," in *Proceedings of the IASS 2024 Symposium. Redefining the Art of Structural Design* (Zürich, Switzerland, 26-30 August 2024) (eds.) P. Block, G. Boller, C. DeWolf, J. Pauli, and W. Kaufmann (Madrid, Spain: International Association for Shell and Spatial Structures (IASS), 2024), 1-17.

27. C. Marzo, and N. Risale, "Stereotomic Design: The Use of Stone in Contemporary Architecture," *Key Engineering Materials* 848 (2020): 165-173.

28. G. Fallacara, and M. Barberio, "An Unfinished Manifesto for Stereotomy 2.0." *Nexus Network Journal* 20 (2018): 519-543.

Architects and the Block Research Group in 2020 in Venice[29] (Figure 5e) and *Hexastone*, designed by Michael Hermann and Benjamin Spaeth and fabricated by the company Vertico[30] (Figure 5f).

There are also a few examples of effective contemporary architectures that have been designed and realised according to stereotomic principles.

The *Bureaux SNBR*, designed by Giuseppe Fallacara and completed in 2015, is an office building for the company SNBR, located in Saint-Savine, near Lyon (France). The structure is composed of four diaphragm stone arches that bear a gable roof. The arches have been conceived stereotomically and the static performance has been optimised through the use of S-shaped joints, that increase the friction among the ashlars[31] (Figure 6a).

The detail of the S-shaped joint has been reprised in another contemporary stereotomic architecture: the Saint-Dizier Market, realised in 2023 by studiolada. It is a parallelepiped structure with external walls made of self-bearing stone masonry. It is characterised by large arched openings with a variable catenary profile, conceived stereotomically. The largest ones present an S-shaped profile like the one adopted in the Bureaux SNBR[32] (Figure 6b).

29. S. Bhooshan, V. Bhooshan, A. Dell'Endice, J. Chu, P. Singer, J. Megens, et al. "The Striatus bridge. Computational design and robotic fabrication of an unreinforced, 3D-concrete-printed masonry arch bridge," *Architecture, Structure and Construction* 2 (2022): 521-543.

30. A. Brodmann, E. Damtsas, C. Schult, B. Spaeth, and Herrmann, "DesignBuild Project of a 3D Printed Concrete Shell with a Segmented and Stereotomic Construction Concept," in *Data-Driven Intelligence - Proceedings of the 42nd Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe 2024)* (Nicosia, Cyprus, 11-13 September 2024), 1: 104-114 (eds.) O. Kontovourkis, M. C. Phocas, and G. Wurzer.

31. G. Fallacara, *Vers une architecture en pierre. Bureaux SNBR à Troyes: 2008-2015* (Paris: Presses des Ponts, 2015).

32. I. Cavaliere, and A. Valentini, *Collectif studiolada. Architetture credibili per il futuro in pietra* (Rome: Gangemi Editore International, 2025).

Figure 5. *Examples of Experimental Stereotomic Contemporary Structure: a) The Armadillo Vault Realised by the Block Research Group of the ETH Zurich in Venice (Italy) in 2016; b) The Pavilion Stone Matters Realised by AAU Anastas Architects in Jericho (Palestine) in 2017; c) The Hypar Vault Realised by Giuseppe Fallacara and the New Fundamentals Research Group in Saint-Savine (France) in 2017; d) The Flux Vault Realised by Giuseppe Fallacara and Maurizio Barberio in 2017 and Exposed at the Fair Salon Rocalia (France); e) The Striatus Bridge Realised by Zaha Hadid Architects and the Block Research Group in 2020; f) Hexastone, Realised by Michael Hermann and Benjamin Spaeth Together with Vertico*

Source: a) www.armadillovault.com/armadillo-vault, photo by David Escobedo of The Escobedo Group; b) www.domusweb.it/it/architettura/2019/01/02/la-pietra-conta-larchitettura-di-elias-e-yousef-anastas.html; c) photo by Maurizio Barberio; d) photo by Gaz Blanco; e) photo by Naaro, www.zaha-hadid.com/design/striatus/; f) www.vertico.com/projects/hexastone.

A different example of stereotomy used in contemporary architecture is represented by the flat vault realised in 2018 by AAU Anastas Architects for the gift shop of the St Mary of the Resurrection Abbey in Jerusalem[33] (Figure 6c). This flat vault is a clear reprise of the one patented by Joseph Abeille in 1699.[34]

33. D. Hernández, *The Flat Vault / AAU ANASTAS* (ArchDaily, 2018).

34. I. V. Miodragovic, and T. Kotnik, "Geometric Versatility of Abeille Vault. A Stereotomic Topological Interlocking Assembly," In *Complexity & Simplicity - Proceedings of the 34th International*

Figure 6. *Some Examples of Contemporary Architectures in which Stereotomy has been used: a) The Bureaux SNBR by Giuseppe Fallacara; b) The Saint-Dizier Market by Studiolada; c) The Gift Shop of the St Mary of the Resurrection Abbey in Jerusalem, Designed and Realised by AAU Anastas Architects*
Source: a) photo by Gaz Blanco; b) www.studiolada.fr/projet/marche-couvert-saint-dizier; c) photo by Mikaela Burstow, www.archdaily.com/903127/the-flat-vault-aau-anastas.

The main challenge with the realisation of stereotomic structures is the need for custom centrings, which have a great impact on costs, waste production and on the assembly complexity. Although recent advances in computational design and digital fabrication have expanded and improved architects' possibilities, most existing applications remain limited to experimental pavilions, bridges or demonstrators and only a relatively small amount of research has explored their potential for modular post-disaster housing. This gap has been specifically addressed in the design process of DuSTcube.

Methodology: The Steps of the Design Process of DuSTcube

The DuSTcube project was conceived as an intersection between Mediterranean ancient construction traditions and needs and contemporary design techniques. Its development follows a design-based approach in which architectural design is employed as a research method to investigate the integration of stereotomic construction rules, Mediterranean vernacular strategies and 3D printing technologies for post-disaster housing. Rather than representing a purely formal design exercise, the project is conceived as an iterative research process in which knowledge derived from literature is translated into architectural solutions and refined through geometric, constructive and environmental considerations.

Conference on Education and Research in Computer Aided Architectural Design in Europe (Oulu, Finland, 24-26 August 2016), 2: 391-397 (eds.) A. Herneoja, T. Österlund, and P. Markkanen.

Mediterranean Climate Conditions

Among the design principles emerging from the literature review, environmental adaptation to the Mediterranean climate played a fundamental role in shaping the architectural proposal. The Mediterranean Area is characterized by mild temperatures, that can reach high peaks during summer. It is fundamental to find strategies that can help reduce energy consumption linked to the use of artificial air conditioning systems. As it was previously described, vernacular Mediterranean architecture is characterised by models that can nowadays be of inspiration for sustainable contemporary solutions. For example, the frequent use of architectural vaults and thick stone walls not only are aesthetic peculiarities but also means to stabilize internal temperatures and optimize airflows. This kind of information helped make the next steps: they became the operative rules through which to reinterpret the housing tradition using both stereotomic principles and contemporary technologies (in terms of design and potential future construction).

The Geometry of DuSTcube and the Application of Stereotomy Rules

The geometric configuration of DuSTcube translates the design principles identified during the research into a buildable stereotomic system. Stereotomy provided the geometric framework for designing self-supporting vaulted spaces with minimal need for temporary supports during assembly, allowing DuSTcube to combine efficiency with modularity and a distinctive architectural identity. Therefore, the housing unit is composed of customised ashlars that can be dry-assembled thanks to their geometric configuration.

Parametric design tools were used to generate the vaulted geometry within a simple cubic volume that was cut through catenary and conical geometries (Figure 7) and then it was discretised into customised ashlars with customised shapes and optimized individual performance.

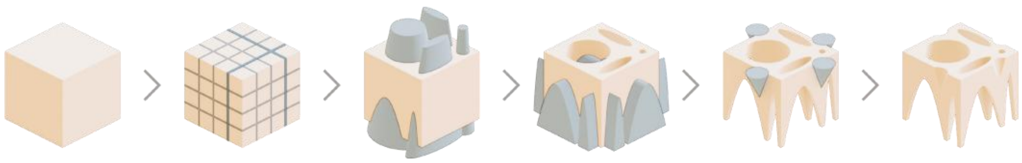


Figure 7. *The Geometric Process through which DuSTcube has been designed*
Source: Drawings by the students Ester Faccilongo, Adriano Marra and Pierfrancesco Uva.

The subtraction and discretisation operations were conceived as part of a stereotomic strategy aimed at generating an architectural project that could be built without conventional centrings and whose stability during construction is supported only by the conical geometry of the internal vaults.

The mentioned subtractions were not driven only by structural and formal considerations, but also by functional requirements. The internal layout has been managed following a strict logic inspired by the previous studies, and sleeping, sanitary and cooking functions have been organised within a 25-square-meter area, maintaining high standards of habitability.

The resulting geometry therefore represents the translation of environmental, structural and functional requirements into a coherent stereotomic architectural system.

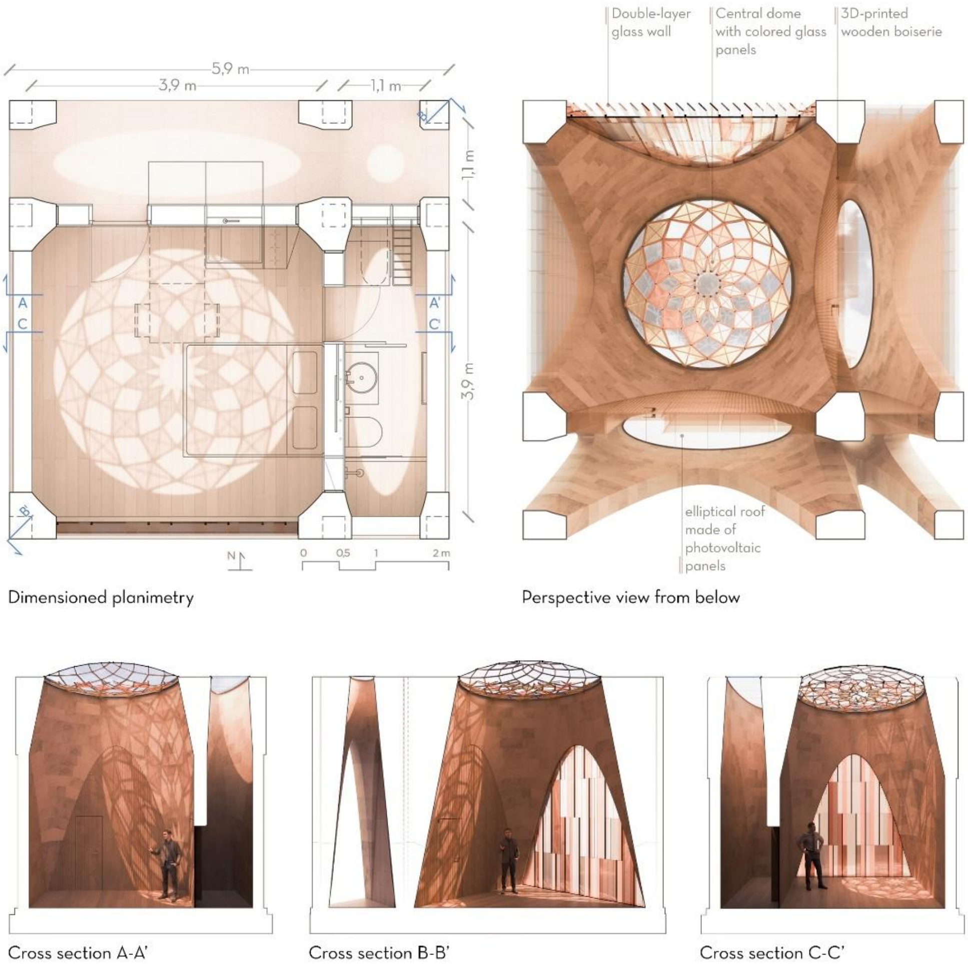


Figure 8. *Technical Drawings: A Dimensioned Planimetry, a Perspective View from Below and Three Cross Sections*
Source: drawings by the students Ester Faccilongo, Adriano Marra and Pierfrancesco Uva.

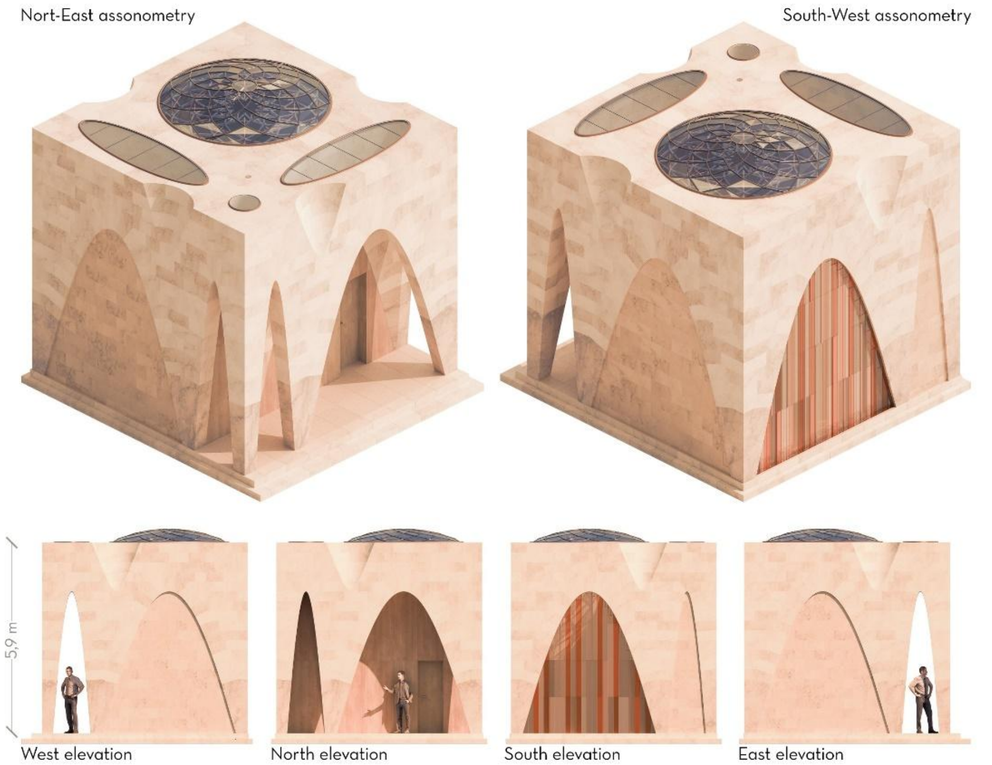


Figure 9. *Technical Drawings: Assonometries and Elevations*
Source: Drawings by the students Ester Faccilongo, Adriano Marra and Pierfrancesco Uva.

Material and Digital Fabrication

The majority of vernacular Mediterranean architecture is built with stone, which is widely available in this geographical area. Since stone is characterised by a high thermal inertia, its use as a construction material can help create comfortable indoor living conditions both in summer and in winter, reducing the need for additional insulating layers. However, a wider use of natural stone for construction would lead to an increase in quarrying activities due to the higher demand and this does not align with the objectives of the Green Deal.

For this reason, it was important to find a new way to work with stone, taking advantage of its properties but avoiding waste and excessive consumption, considering that in 2015 82,6 million tons of stone were produced, but the amount of waste was over 70% of the total.[35] The proposed solution consists of using recycled stone powder instead of traditional quarry blocks, obtaining it both from stone-cutting industry leftovers and from powders derived from collapsed buildings. The 3D printed stone has also been conceived to be recyclable at the end of the building's life cycle, supporting the circularity of the proposed construction process (Figure 10).

35. MICS, *2.04 STONE – SusTainable ecOdesign reusiNg quarring wastE.*

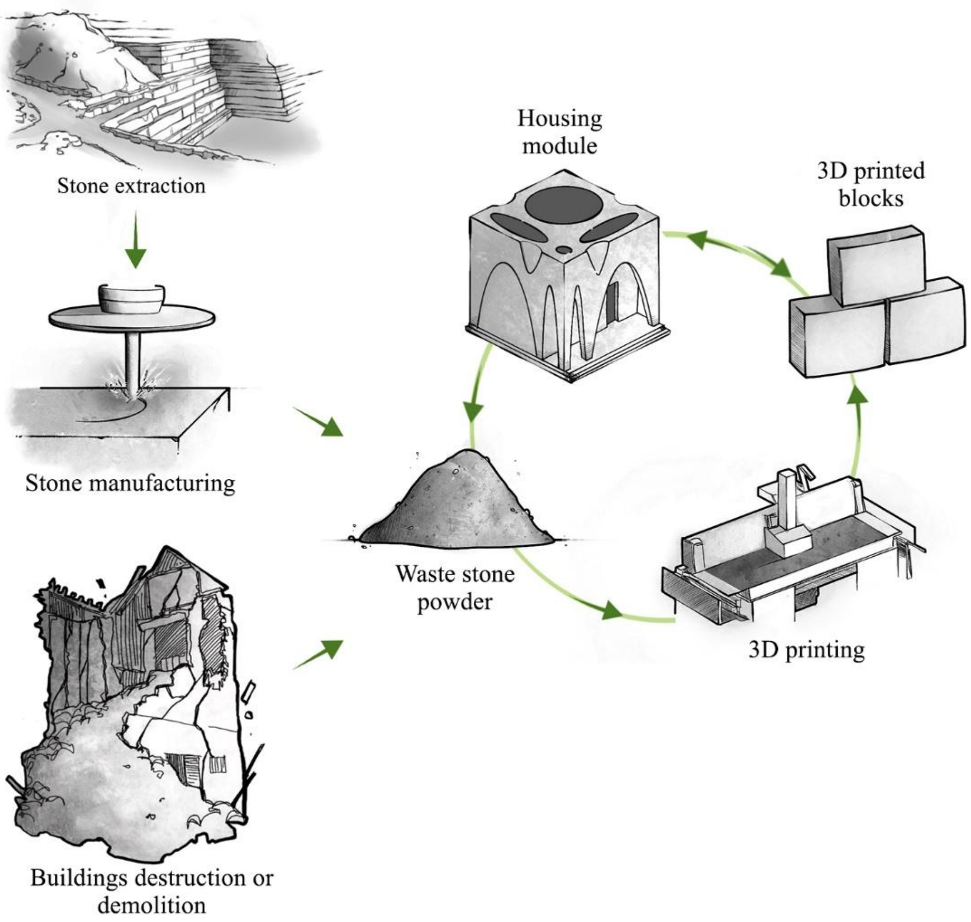


Figure 10. *A Scheme of the Life Cycle of Stone*
Source: Drawing by the author Dario Costantino.

The additive manufacturing technique selected to work with this powder is binder jetting, which allows the precise deposition of a binding agent over layers of stone dust, forming solid objects without the need for high temperatures or heavy moulds. Moreover, working with 3D printing technologies leads to several advantages such as a high degree of customisation (keeping it possible to make variations of a dwelling or of its components without the necessity to produce a lot of formworks or moulds) and a low need of specialised human labour.

In this study, powder of Lecce stone was selected as the aggregate for a hypothetical binder jetting process, primarily for aesthetic reasons. Lecce stone is a light-coloured calcarenite widely found in the Apulia region of southern Italy and has been extensively used in the construction of historical vaulted structures. Preliminary binder jetting experiments have already been carried out using waste Lecce stone powder through a collaboration between Concr3de – a company specialised in additive manufacturing with stone-based powders – and Pimar – an Apulian company specialised in natural stone processing.

Some prototypes exposed at the international exhibition Marmomac Meets Academies in the 2023 and in the 2024 editions –*Technovauld* by Dustin White[36] and *Doppionodo* by Giuseppe Fallacara and Marco Massafra[37] – demonstrate that the appearance of 3D printed stone is very similar to natural stone, keeping this technology very suitable for contemporary architectural applications (Figure 11).

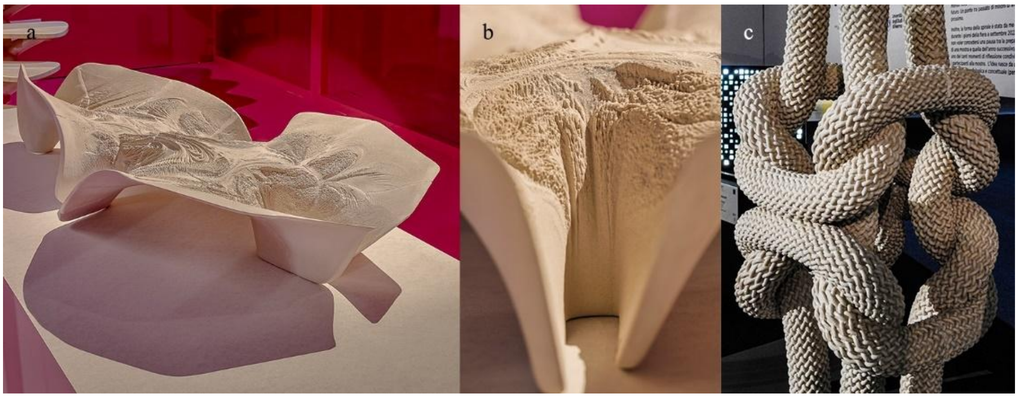


Figure 11. *Some Prototypes Realised through Lecce Stone 3D Printing with the Binder Jetting Technology: a) Technovauld by Dustin White; b) A Detail of Technovauld that Shows the Finishing of 3D Printed Stone; c) Doppionodo by Giuseppe Fallacara and Marco Massafra*
Source: a) and b) photos by Gaz Blanco; c) photo by the authors.

At the current stage of the research, no laboratory tests have been carried out on binder-jetted Lecce stone powder to evaluate its mechanical properties. Nevertheless, Concr3de has published the certified mechanical properties of one of its 3D-printed limestone material.[38] These values were used for a preliminary comparison with the mechanical properties of three different types of Cursi stone, which are a variety of Lecce stone.[39]

The comparison presented in Table 1 should be regarded as a preliminary benchmark intended to provide an indicative assessment of the proposed material rather than a direct validation of its structural performance.

36. D. White, "Technovauld," in *Marmomac Meets Academies. Advanced research, lithic experimentation* (ed.) G. Fallacara (Ferrara: Media MD, 2023), 76-79.

37. G. Fallacara, and M. Massafra, "Doppionodo," in *Ceci n'est pas un fossile. Marmomac Meets Academies 2024* (ed.) G. Fallacara (Ferrara: Media MD, 2024), 62-63.

38. Concr3de's 3d-printed limestone technical sheet available at: https://concr3de.com/material-stone-minerals.php. [Accessed 27 June 2026.]

39. G. F. Andriani, and N. Walsh, "Petrophysical and mechanical properties of soft and porous building rocks used in Apulian monuments (south Italy)," in *Natural Stone Resources for Historical Monuments* (eds.) R. Přikryl, and Á. Török (London: Geological Society, Special Publications, 2010), 129-141.

Table 1. *The Comparison between the Mechanical Characteristics of 3D Printed Limestone and Three Types of Natural Lecce Stone*

Material	Density [kg/m³]	Compressive strength [MPa]	Flexural strength [MPa]	Porosity [%]
3D printed limestone	1650	12-31	3-6	30
Hard Cursi stone	1500-1900	16.7-22.7	3.3-5	30-44
Dolce Cursi Stone	1500-1700	12.8-15.5	3.1-3.9	37-44
Gagginara Cursi Stone	1500-1600	11.3-18.3	1.6-3.2	41-44

The comparison shows that the 3D-printed limestone exhibits density, compressive strength and flexural strength values that are generally comparable with those of natural Lecce stone. In particular, the printed material displays a slightly lower average porosity, while its compressive and flexural strengths may reach values higher than those reported for the natural stone. These results may be influenced by several process parameters, including the orientation of the applied loads with respect to the printing layers and the selected layer thickness. In this regard, a study conducted by the Shandong University of Science and Technology found that, in the case of 3D-printed sandstone mixtures, the mechanical performance varied according to the deposited layer thickness, with the highest strength values obtained using a 0.2 mm layer and progressively lower values for 0.3 mm and 0.4 mm layers.[40] Although sandstone differs from limestone in terms of mineralogical composition, it is reasonable to assume that a similar trend may also apply to limestone-based mixtures, since the mechanical behaviour of binder-jetted materials depends not only on the aggregate but also on the characteristics and distribution of the deposited binder. For this reason, it is also considered reasonable, as a preliminary assessment, to use the certified mechanical properties of Concr3de's 3D-printed limestone as a reference, even though its aggregate is not composed of Lecce stone powder.

3D printing also gives designers the possibility of calibrating the porosity and density of each block according to the results of structural simulations optimising material distribution according to stress conditions (Figure 12). Therefore, the densest blocks can be strategically positioned where higher stresses are expected.

40. Q. Xu, L. Jiang, C. Ma, Q. Niu, and X. Wang, "Effect of Layer Thickness on the Physical and Mechanical Properties of Sand Powder 3D Printing Specimens," *Frontiers in Earth Science* 21 (2021): 1-11.

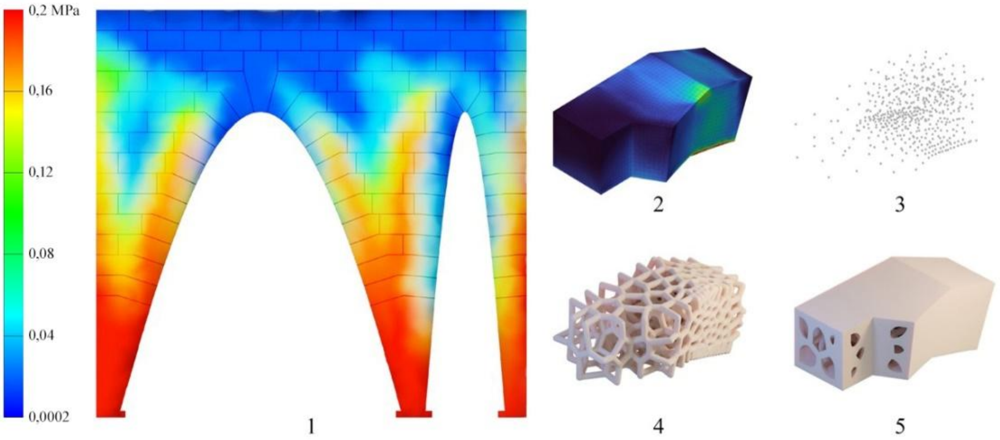


Figure 12. *A Scheme of the Variation of Porosity of the Stone Ashlars according to Stresses 1) The Von Mises stresses of the entire structure are calculated through a finite elements analysis; 2) the stresses inside each single ashlar are calculated; 3) the volume of the ashlars is used as the domain for a point cloud whose density changes according to the intensity of the stresses; 4) the points of the point cloud are connected one another to form a lattice grid, which represents the filling of the ashlars; 5) the faces of the ashlars are closed using surfaces*
Source: drawings by the students Ester Faccilongo, Adriano Marra and Pierfrancesco Uva.

Assembly Process and Constructive Efficiency

The construction of DuSTcube has been conceived to be as fast and straightforward as possible, since it was designed for post-disaster contexts where skilled labour may be limited and rapid construction is required. For this reason stereotomy was extremely useful, since blocks were designed to interlock and self-stabilise through geometry alone. As a matter of fact, this housing unit was conceived to be assembled through a dry construction process, with the individual blocks being dimensioned to avoid excessive weight during manual handling. Moreover, the absence of mechanical fasteners or joints would also simplify potential disassembly, reuse and relocation operations. Of course, for safety reasons, a structural stabilisation system based on post-tensioned cables was incorporated into the design. The cables originate from the foundation and run through the entire height, contributing to the overall stability of the unit (Figure 13).

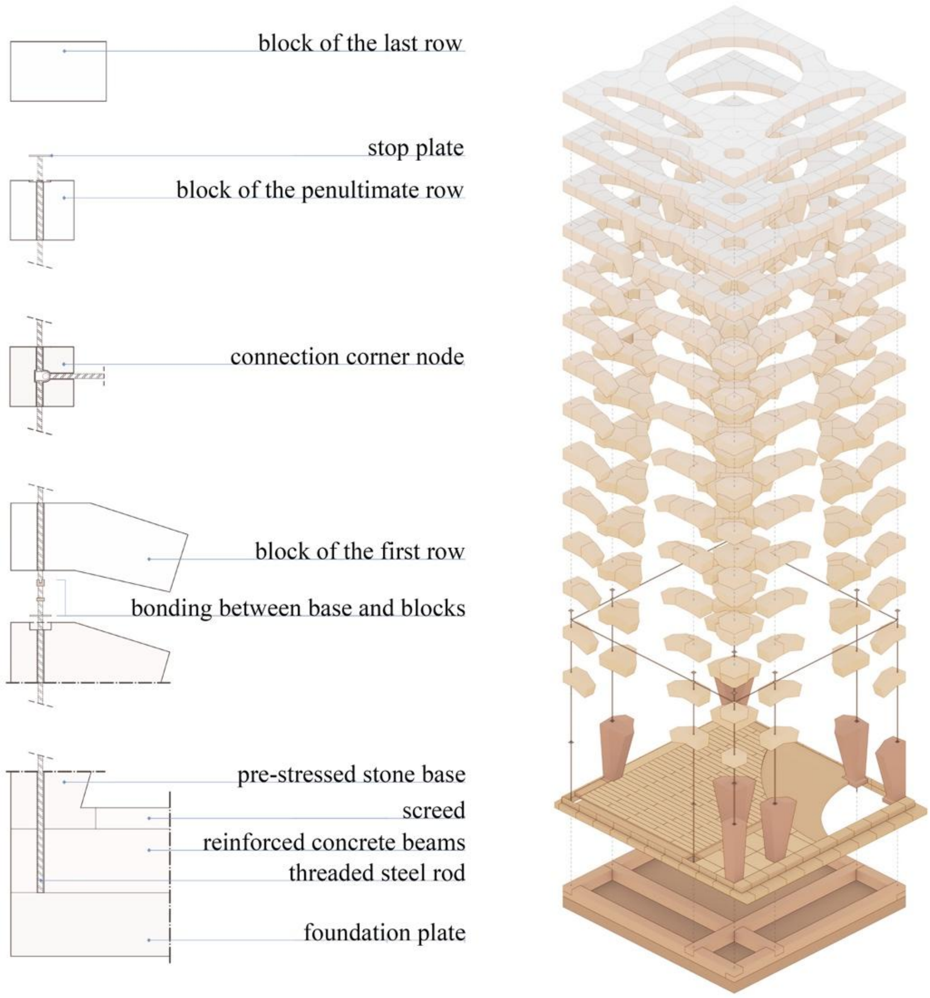


Figure 13. *A Scheme of the Subdivision into Ashlars, in which the Post-Tension Cables are Visible*
Source: drawings by the students Ester Faccilongo, Adriano Marra and Pierfrancesco Uva.

The proposed assembly sequence begins with the preparation of a levelled foundation slab onto which the lower ashlars are positioned. As the blocks are progressively printed and placed – depending on the production strategy, the blocks could be either prefabricated or printed close to the construction site –, each course follows the conical geometry of the vaults, allowing the structure to stabilise incrementally during construction. The roofing elements were also conceived to be produced through additive manufacturing and designed to integrate solar panels and, where required, passive ventilation chimneys.

This approach has the potential to reduce logistical requirements and dependence on large industrial infrastructures, allowing either prefabrication and transport of complete housing units or the local production of individual components whenever suitable manufacturing facilities are available.

Moreover the modular nature of the system allows multiple units to be aggregated into larger settlements suitable for both reconstructed neighbourhoods and small-scale communities (Figure 14).

Figure 14. *Rendering of a Settlement Made of DuSTcube Units*
Source: drawing by the students Ester Faccilongo, Adriano Marra and Pierfrancesco Uva.

Eventually, furniture was also considered an integral part of the design process. The internal components were conceived as deployable elements that could potentially be fabricated using wood powder-based additive manufacturing technologies, providing greater flexibility in the organisation of the interior spaces while optimising the use of the 25-square-metre module (Figure 15). The choice of wood for the furnishings deliberately introduces a visual and material contrast with the stone envelope, softening the perception of the interior spaces and contributing to a more welcoming domestic environment. This combination seeks to balance the robustness of the stereotomic structure with the spatial comfort expected of a permanent dwelling rather than an emergency shelter.

Figure 15. *Rendering of the Interior of a DuSTcube Unit*
Source: drawing by the students Ester Faccilongo, Adriano Marra and Pierfrancesco Uva.

Benefits of the Design Proposal and Sustainability Strategies

From an environmental standpoint, the proposal addresses several contemporary challenges of sustainability and green design, seeking to reduce embodied energy, construction waste and polluting materials such as cement. Moreover, the thermal inertia provided by the predominant use of stone-based components has the potential to contribute to natural cooling in summer and heat containment in winter, reducing energy consumption due to artificial conditioning systems.

The central portion of the roof was conceived as a system of semi-transparent photovoltaic glazing connected to an automated shading mechanism. The concept envisages movable glass layers that move in relation to the progression of the sunlight, providing dynamic shading while contributing to renewable energy production (Figure 16).

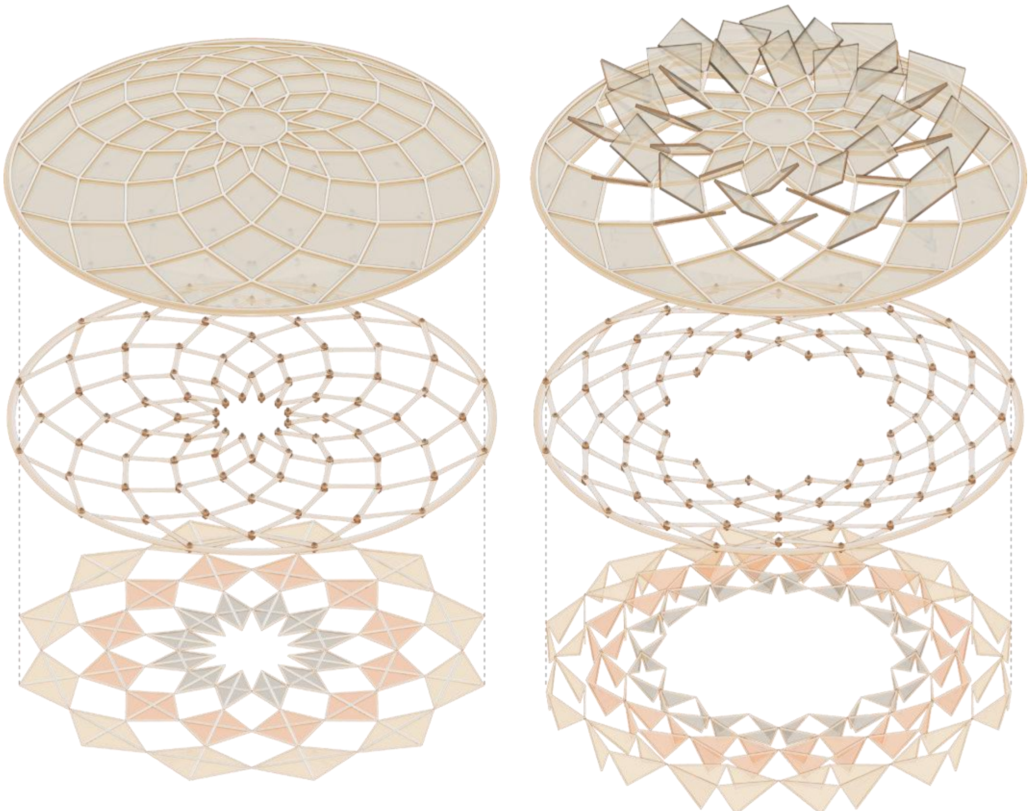
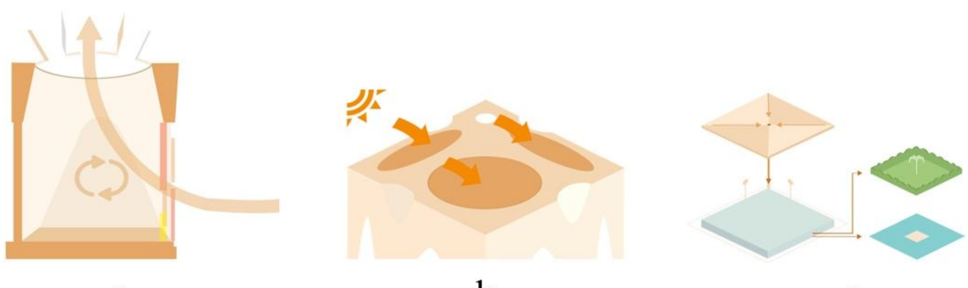


Figure 16. *Scheme of the Functioning of the Glass Window that Covers the Central Space*
Source: drawing by the students Ester Faccilongo, Adriano Marra and Pierfrancesco Uva.

Furthermore, the central roof opening was designed to support passive ventilation strategies such as the stack effect to favour the reduction of artificial cooling and heating systems (Figure 17a). The glass is thought to be photovoltaic, in order to contribute to the efficiency of the structure through the production of clean energy (Figure 17b). Finally, the possibility of collecting rainwater was considered, therefore the roof has a slight slope aimed at letting water flow towards a vertical pipe that brings it to an underground tank (Figure 17c).



a b c

Figure 17. *Schemes of the Sustainability Strategies Adopted: a) The Stack Effect; b) Energy Production through Photovoltaic Glass; c) Rainwater Collection and Reuse*
Source: drawing by the students Ester Faccilongo, Adriano Marra and Pierfrancesco Uva.

Besides technical aspects linked to sustainability strategies, the proposal also carries a layered cultural value. On the one hand, the combination of stereotomy, vaulted geometries and local materials encourages an aesthetic and formal reconnection with the Mediterranean architectural tradition, fostering continuity between new housing solutions, historical building practices and the geographical specificities of the region. On the other hand, the integration of contemporary digital tools introduces new ways of conceiving architecture and enables more strategic design processes, reducing construction time, costs and labour requirements. Furthermore, the modularity and the digital reproducibility of the components make the system scalable, adaptable and easily customisable according to needs or cultural contexts. Finally, the proposed system is conceived as an open and upgradeable framework, capable of evolving alongside future developments in materials and construction technologies.

Discussion: Limitations and Challenges

DuSTcube responds to a broad range of needs that arise in post-crisis contexts, particularly within the Mediterranean basin. Rather than being conceived as a simple shelter, it represents the result of a layered design process that proposes a new interpretation of contemporary reconstruction. In this perspective architecture is intended not only as a means of rebuilding what has been lost, but also as a tool for restoring a sense of place, identity and continuity.

However, despite its conceptual and methodological potential, DuSTcube is currently at the design stage and has only been investigated through simulations and small-scale physical prototypes (Figure 18).

Figure 18. *The Two Realised Maquettes*
Source: photos by the students Ester Faccilongo, Adriano Marra and Pierfrancesco Uva.

Several challenges must still be addressed before the proposal can be translated into a full-scale construction system. The transition from small-scale prototypes to real applications may significantly affect structural behaviour, construction logistics and material performance. Furthermore, the long-term effects of environmental agents, such as humidity and ultraviolet radiation, on binder-jetted stone components still require experimental investigation. At the current stage, only a limited number of elements have been fabricated using Lecce stone powder, and the optimisation of the binder formulation remains an important objective for future research.

Another important challenge concerns the complexity of both stereotomic design and customised blocks, which currently require specific tools and digital skills that may not always be available, particularly in post-disaster contexts. Future developments should therefore focus on the implementation of open-source parametric tools, predefined block libraries and codes capable of simplifying and accelerating design operations.

A further limitation is represented by the current cost and limited diffusion of technologies such as large-scale 3D printing and automated building components. Their wider adoption will largely depend on future technological developments and increasing accessibility within the construction sector.

Finally, logistical aspects still require further investigation, particularly regarding the coordination of design, production, transportation and assembly processes. Since both the proposed materials and construction techniques remain unconventional, defining an efficient operational framework will be essential for future implementation. Although emergency situations inevitably prioritise speed and functionality, DuSTcube is not conceived as a temporary shelter but as a long-term architectural solution intended to support the regeneration of destroyed settlements and the reconstruction of stable communities.

Future research will therefore focus on the experimental validation of the proposed construction system through mechanical testing, full-scale prototyping and long-term performance assessment, completing the design-based research framework presented in this study.

Conclusions

The DuSTcube project proposes a radical yet grounded model for post-crisis architecture in the Mediterranean world. By integrating ancient construction principles with contemporary digital design and fabrication technologies, it explores the potential of a modular dwelling that combines sustainability, cultural continuity and constructive efficiency.

Although the research is currently limited to the design stage, it establishes a methodological framework for the integration of different disciplines and tools, such as stereotomy and 3D printing, within the field of post-disaster housing. Even if its current limitations are clear and explicit, they do not discredit the concept, rather they underline the necessary work that must be done in order to translate the conceptual and theoretical design into experimentally verified building systems.

Future developments will therefore focus on the experimental validation of the proposed construction system through material characterisation, mechanical testing and full-scale prototyping, allowing the design assumptions presented in this study to be verified and further refined.

In a world increasingly affected by conflicts, forced migration and climate-related disasters, DuSTcube represents a research-driven architectural vision that seeks to reconcile innovation, sustainability and Mediterranean architectural identity, contributing to the ongoing debate on resilient and culturally responsive post-disaster reconstruction.

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