Layer by Layer

Exploring Opportunities for Large-Scale Additive Manufacturing in Heritage Preservation

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Abstract

The present work is the result of a five-month graduation project on the topic of Large-Scale Additive Manufacturing and its potential for added value creation in the preservation of architectural heritage.

The project is made up of two distinct sections prefaced by a short introduction that contextualizes Large-Scale AM within heritage preservation. The first section dives into the theoretical principles behind each discipline, setting the groundwork for a later, more in-depth analysis of their needs and opportunities. This is done through a series of case studies on first, Adaptive Reuse projects (Adaptive Reuse being a sub-discipline of preservation), and second, Large-Scale AM projects. The AR case studies help to understand other designers and architects' approaches to Adaptive Reuse, while the LSAM case studies are used to extract a series of features unique to Large-Scale Additive Manufacturing that present potential for added value creation in a preservation project. This section concludes with the mapping of these features to the 3D printing principles that enable them, as well as a series of factors that affect the potential success of Adaptive Reuse projects.

The second section aims to apply this theoretical framework to a real-world case. In it, a site is chosen based on a series of suggestions resulting from the earlier part of the research. The site is then visited and analyzed in an effort to understand its cultural, historical, and architectural significance. The results of this analysis are condensed into a series of design inputs that inform the design of an intervention which proposes the revamping of the site. Finally, the intervention is designed and broken down into its core principles, concluding with a reflection on the potential of Large-Scale AM in the preservation field.

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Glossary

LSAM	Large-Scale Additive Manufacturing
AM	Additive Manufacturing
3DP	3D Printing
CAD	Computer-aided design
CAM	Computer-aided manufacturing
Layer height	Vertical thickness of 3D-printed layers
Layer width	Horizontal thickness of 3D-printed walls
Toolpath	Path followed by 3D printer to produce three-dimensional geometries
Extrusion rate	Amount of material extruded per unit of time by 3D printer
Adaptive reuse	Repairing and adapting existing buildings to fulfill a different purpose
Revamping	Renovate, modernize, repair
Vernacular	Traditional reginal architecture
Typology	Refering to the essential architectural characteristics of a building
Materiality	Refering to the formal qualities resulting from the use of a particular material

Part I
Setting the stage

Introduction

We are on the brink of the *Fourth Industrial Revolution*, an event characterized by a fusion of technologies that blurs the line between the digital and physical world (Schwab, 2016). As technology advances, the way we design, build, and rebuild the world around us changes. When it comes to preserving our cultural heritage, this technological shift invites a creative interpretation of how modern tools might harmonize with traditional building techniques.

This graduation project explores how Large-Scale Additive Manufacturing (LSAM) can dialogue with traditional craftsmanship through interventions that honor a building's cultural legacy while enhancing its long-term resilience. It focuses on Adaptive Reuse as a preservation strategy that balances authenticity with modern living standards, analyzing the value created in exemplary Adaptive Reuse projects and mapping it to opportunities created by LSAM in architecture and product design, finding AM-enabled solutions to problems in preservation.

The results of this theoretical research are applied to a real-world case study in the island of Thirasia, in Greece. An in-depth cultural, historical, and typological analysis of the site is carried out in order to understand its heritage value and propose an intervention that helps preserve and enhance it. Finally, this intervention is designed according to the conclusions of the analysis and a demonstrator is produced as a proof of concept that embodies all aspects of the intervention.

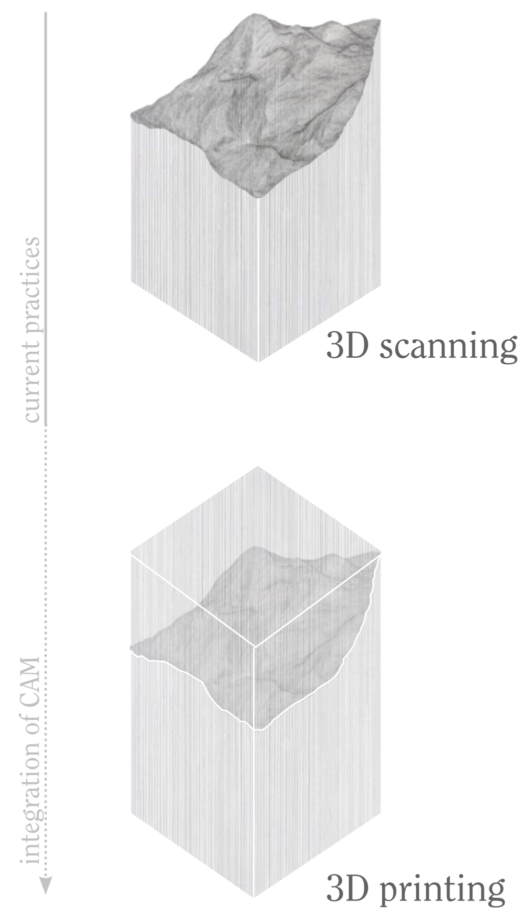


Figure 1. Integration of digital fabrication as a next step in the current preservation workflow.

A gap in the digital preservation workflow

In recent years, heritage preservation has been embracing modern technologies for their precision and efficiency in documentation. The Declaration of Cooperation on Advancing Digitization of Cultural Heritage (European Council, 2019) highlights the *"urgent need to make the most of digital technologies to record, document and preserve Europe's cultural heritage"*, with European Heritage expected to be fully digitized by 2025. However, digital tools in preservation are, at present, mostly confined to the archival of three-dimensional records of European Heritage. While the existence of these digital records is crucial for the monuments' conservation, analysis, and general availability for educational purposes, it also begs the integration of digital manufacturing tools into the repair and reuse of these monuments. It seems only natural that digital models are translated into physical ones through the integration of AM into the now digital workflow of preservation and restoration, especially as we are already seeing this being done in so many other disciplines.

Problem definition and contextualization

The new master-builder

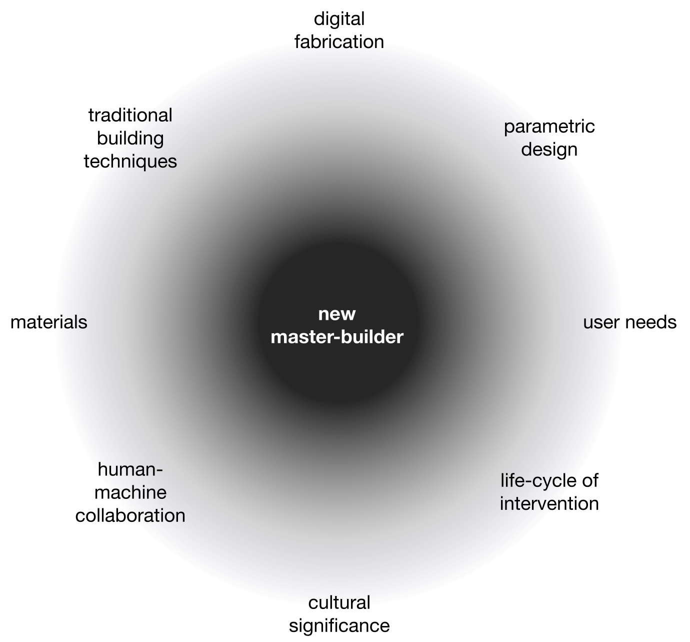


Figure 2. The new master-builder as a supervisor of design and preservation projects. Visual adapted and expanded from Codarins (2020)

Codarins (2020) identifies an optimization margin in preservation efforts derived from the availability not only of digital records, but also production tools capable of reducing the complexity of the production chain of custom architectural elements. Moreover, she highlights that preservation projects are unique and site-specific, meaning that customized solutions are required on a case-by-case basis. This is traditionally achieved by highly-skilled, local craftsmen who are able to produce detailed and unique reconstructions of the original building fragments. However, already since the mid-20th century, a mixture of educational, economical, and societal factors has led to the gradual disappearance of craftsmen and, with them, their knowledge of traditional building techniques (Bourdieu, 1984).

The Fourth Industrial Revolution proposes a reinterpretation of the role of the master-builder, as a synthetic figure between the multiple actors and techniques involved in the increasingly complex building process (Codarin, 2020). In this role, the designer/ master-builder has a comprehensive overview of the problem and understands both traditional and digital craftsmanship, as well as users' changing needs, the cultural significance of heritage buildings, and the impact of interventions carried out on said buildings along their entire life cycle.

Designers and architects in the Fourth Industrial Revolution therefore need to have a thorough understanding of modern construction techniques; not only of how these can mimic traditional ones, but how they can work together with them to add value to interventions. Yes, artisanship is being lost and there is an urgent need for alternative methods of preservation, but this problem also creates opportunities. Opening up the preservation space to new technologies warrants a creative reinterpretation of preservation, one that is synchronous with our present time – which is when the intervention is carried out and therefore constitutes just another layer in the history of the site.

Figure 3. Additive Manufacturing in restoration. From top to bottom: restoration of the Arch of Palmyra (Secchi, 2016), replacement gargoyle for the Notre Dame cathedral (Concr3de, 2019), and ornamental column restoration (Khan, 2016)

Creating value in preservation

Additive Manufacturing is known for its ability to accurately reproduce complex geometric forms and has been used in monument restoration specifically for this purpose. When it comes to historical monuments, there is little room for creativity, given their cultural significance. In this vein, there are some notable examples of AM in restoration, such as the famous replication of the Arch of Palmyra and proposals for the restoration of the Notre Dame cathedral using binder jet printing – even research done within the TU Delft by Ali Sarman Khan, who focused on the patching of ornamental heritage through 3D scanning and printing.

The interventions designed in these projects all share the same lack of protagonism in the context where they are applied. They are meant to function as scaffolding, as a frame that supports and highlights the original monument, allowing people to imagine what it must have looked like in the past. However, moving away from monuments and into a realm that allows for more creative reconstructions, AM can be explored as more than scaffolding. Tangible cultural heritage includes not just monuments, but a plethora of architectural works that hold more value as functional living spaces than museum pieces. As such, their preservation involves refurbishment and adaptation to modern needs and standards.

Although its architectural applications hold much promise, within the context of preservation, LSAM has scarcely been explored in its potential to create additional value as a novel building technique. This research sets out to explore the potential for Large Scale Additive Manufacturing for the creation of said additional value in the simultaneous preservation and adaptation of architectural heritage.

Contextualizing preservation and digital fabrication

In his research, Khan (2016) identifies an opportunity space for digital fabrication techniques in preservation according to the degree of intervention needed, adding that *"digital fabrication is independent of these degrees of intervention and can be used as a tool by conservationists for any appropriate degree of intervention, but primarily when additional material is required"*. Based on this initial contextualization of LSAM within preservation, we begin to establish the boundaries of the space within which this project takes place.

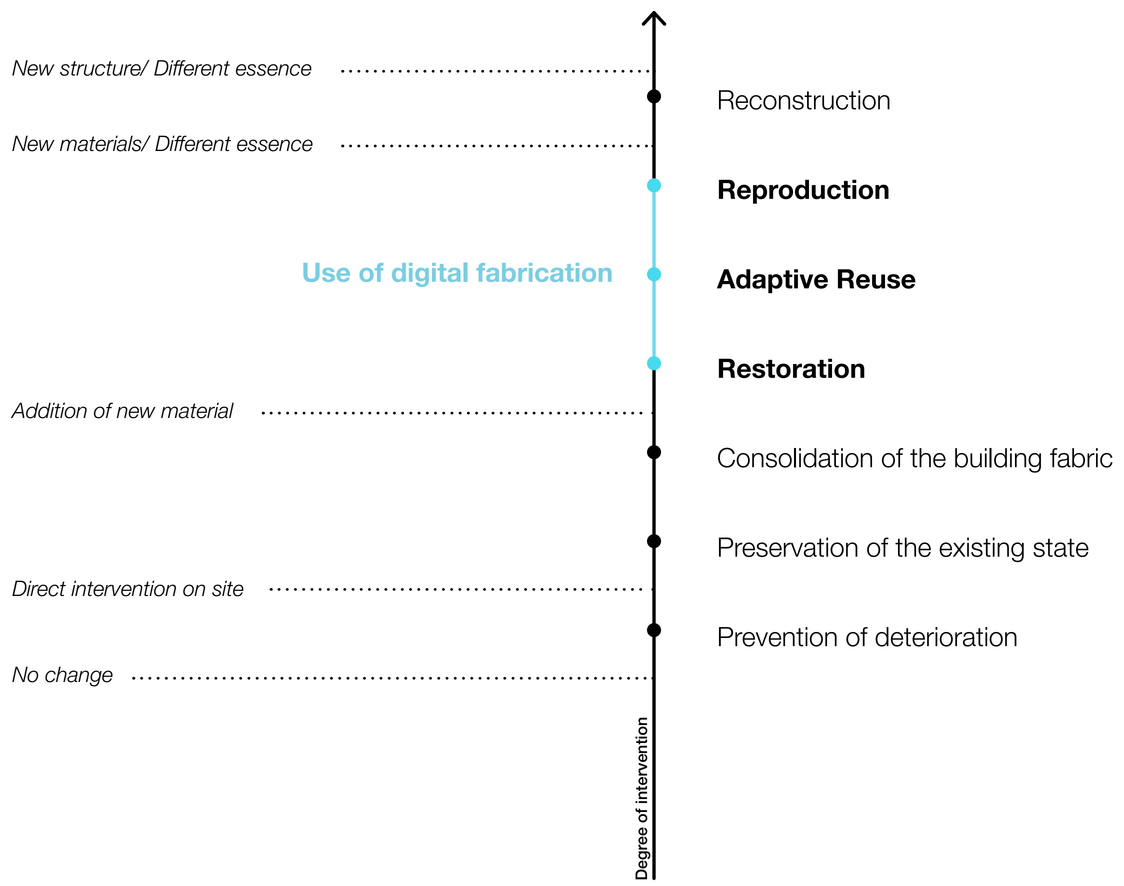


Figure 4. Contextualization of digital fabrication within preservation according to the increasing degrees of intervention. Visual adapted from Khan (2016)

Research questions

In order to paint an accurate picture of the design space that encapsules both LSAM and preservation, they must first be understood as disciplines in their own right. In order to do this, three background questions precede the main research question. These aim to give a clearer understanding of the problems within heritage preservation and reuse, the state of the art of Large-Scale AM in architecture, as well as the potential of LSAM in its integration into current preservation efforts and its role within them.

Background questions

These first three background questions help guide the first part of the research, the aim of which is to identify theoretical opportunities for LSAM in heritage preservation.

They serve to effectively understand both preservation and Additive Manufacturing as disciplines in their own right and establish meaningful connections between them.

1. *What is cultural heritage and how is it currently being preserved and adapted for new uses?*
2. *What opportunities does LSAM currently offer in architecture?*
3. *How could LSAM theoretically address some of the problems identified in preservation?*

Main research question

It is important to first answer the background questions. Upon doing so, we can form an image of the problem space in which we are operating and can speculate as to what the answer to the main question is.

The speculative answer to this question must, however, also be tested in practice.

Synthesized, the background questions result in the main research question of the project:

"How can large-scale additive manufacturing be used to create additional value in the preservation of built heritage?"

Methodology

The project starts with some extensive, theoretical desk research, and is followed by a site-specific case study where the knowledge generated in the first part is applied. Halfway between the two are the midterm results of the project, which culminate in a design tool that informs the practical application of the theoretical research.

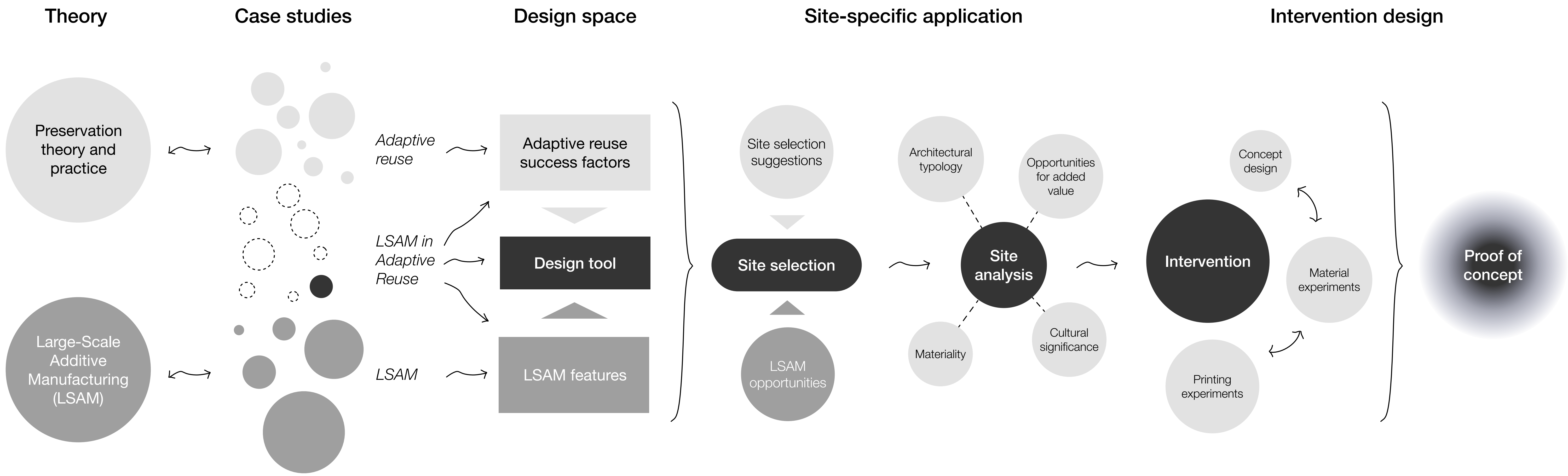
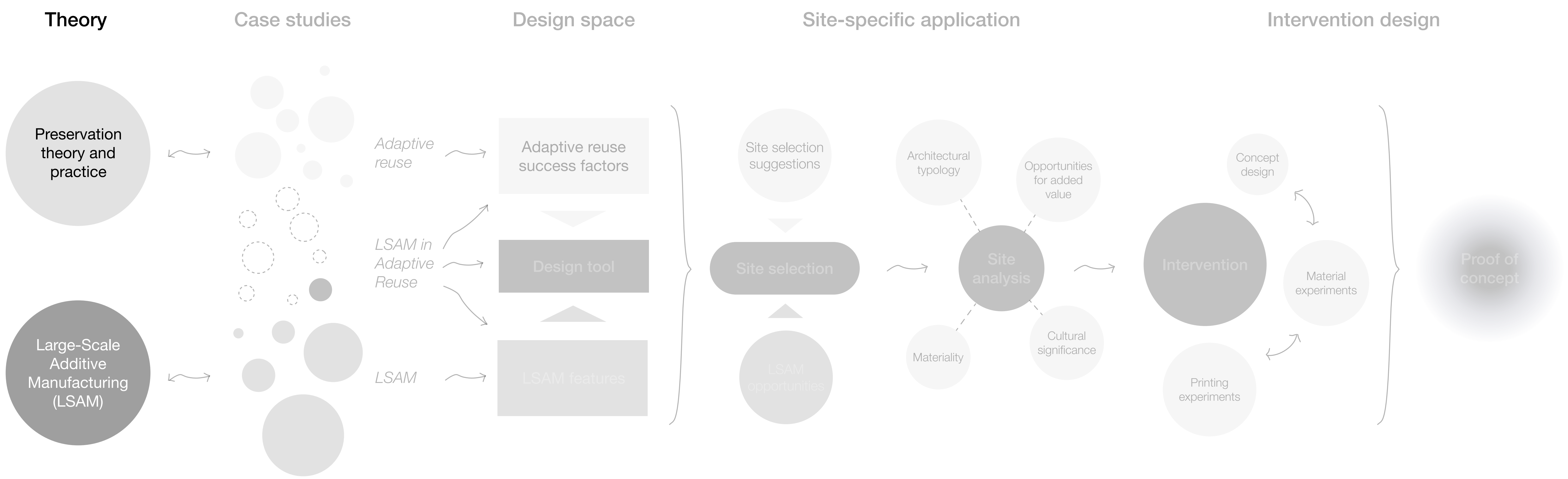


Figure 5. Project methodology

Theory

Led by the background questions posed above, the theory is split into the two disciplines that the project attempts to combine: *preservation and Large-Scale Additive Manufacturing*.

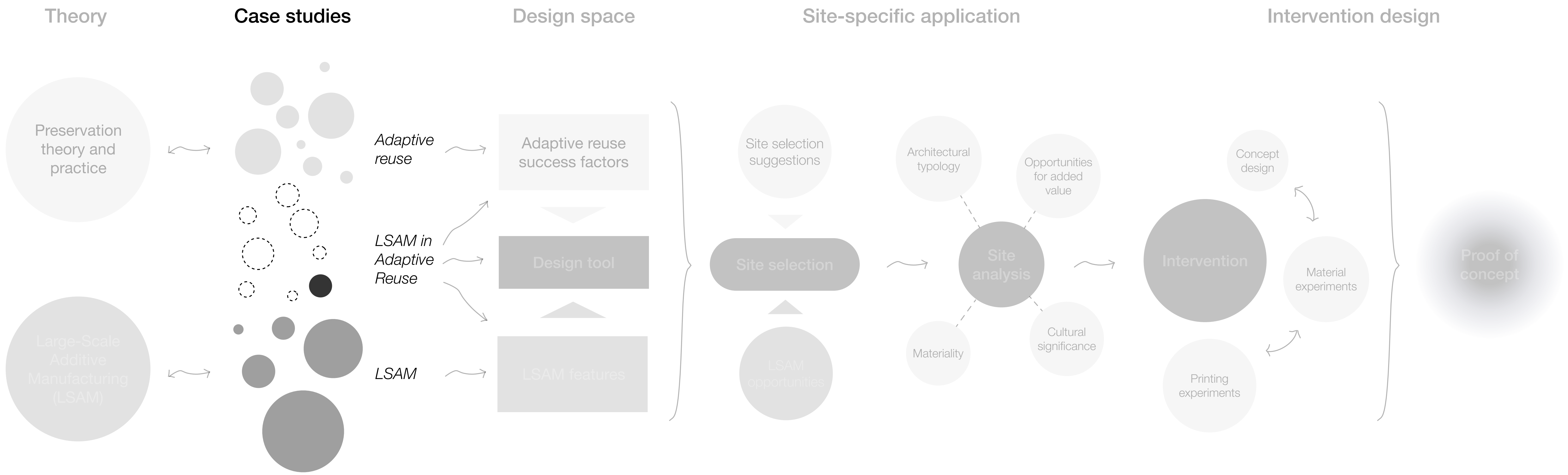
Preservation as a discipline is complex, diverse in terms of approaches, and often controversial. Its diversity must be understood in order to place the project correctly within it and suggest a type of intervention that is respectful to the discipline and cultural heritage as a whole. In this theory, a series of factors are identified that are used in the field to evaluate the success of an Adaptive Reuse project (Adaptive Reuse being a sub-discipline of preservation). At the same time, a brief introduction to LSAM is needed to understand the basic principles behind it and, therefore, its limitations and opportunities.



Case studies

In order to understand the opportunities offered by LSAM, as well as those allowed by preservation, a state-of-the-art research is done through case studies. In this phase, both disciplines are still studied separately (with the one exception), as there have not yet been attempts at combining them.

Adaptive Reuse case studies are used to evaluate how designers and architects have dealt with the problems of preservation and adaptation in a wide variety of contexts, while LSAM case studies are used to identify features unique to Additive Manufacturing that can be applied in an architectural context and, consequently, to the reuse of built heritage, creating additional value in preservation efforts.

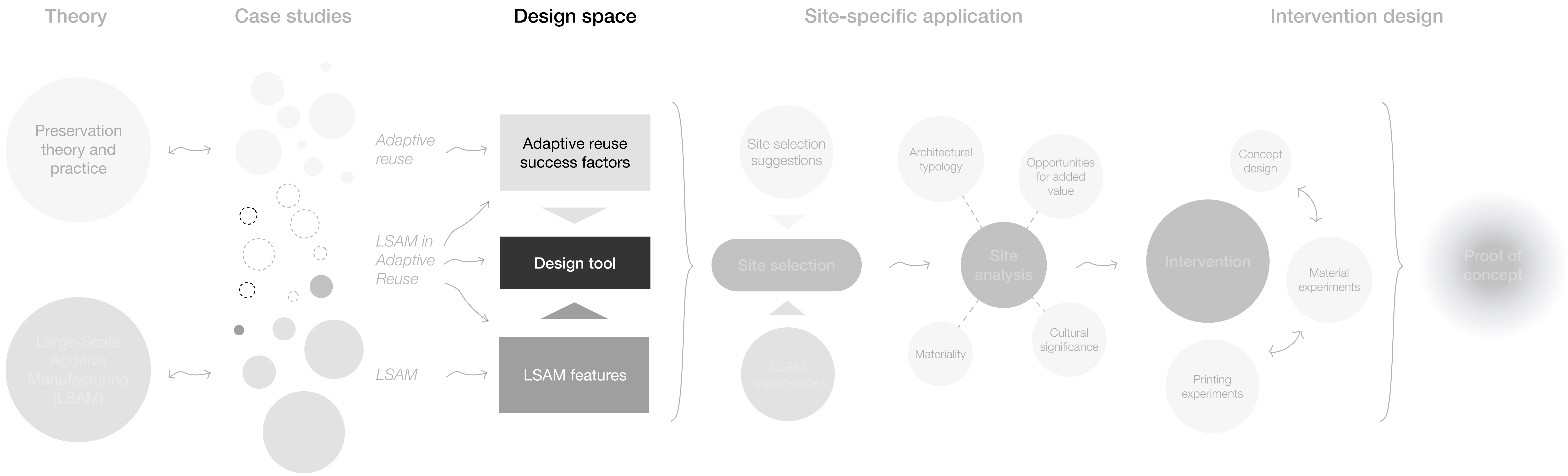


Design space

Apart from each other, the theory and case studies inform the design space within which the project operates.

The conclusions from each half of the research are boiled down to two sets of variables: *success factors in the case of Adaptive Reuse, and opportunities (or features) in the case of LSAM*. On the one hand, we identify the factors that influence the success of an Adaptive Reuse project, interpreting them as opportunities for focused interventions; on the other, we extract features unique to 3D printing that could help address problems in preservation.

This way, we find that in the intersection of both these disciplines lies an opportunity space that can be visualized as a design tool. This tool can then be used as a starting point when analyzing a site and identifying opportunities for added value in its repair and reuse.

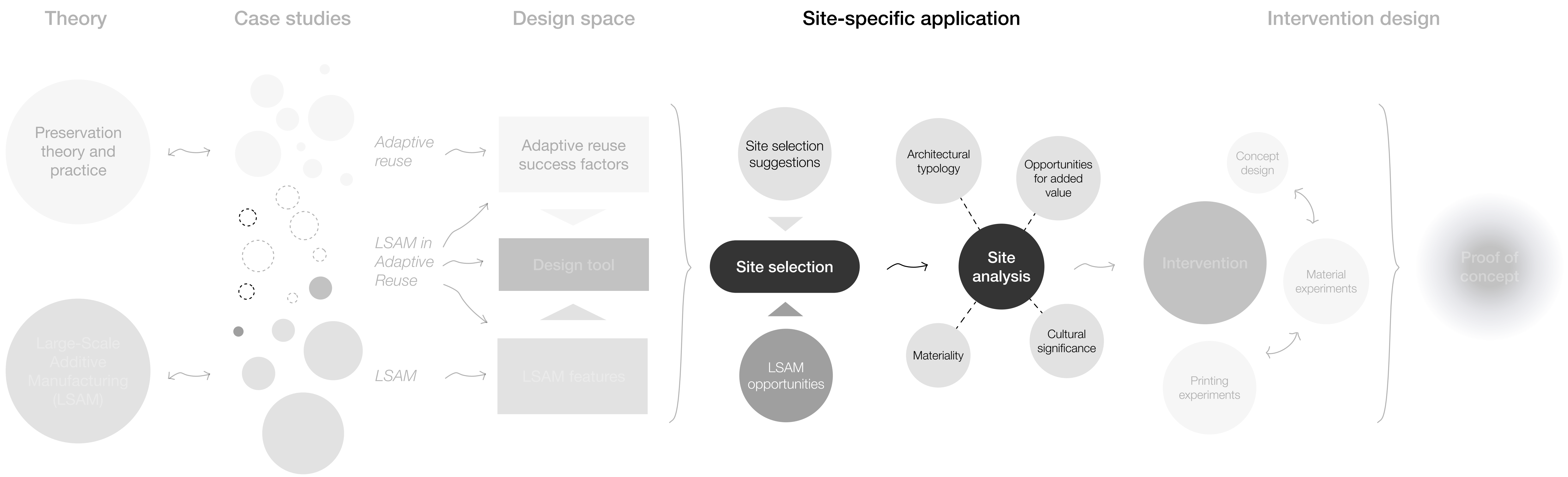


Site-specific application

Using the design tool resulting from the previous phase, an evaluation of proposed sites is done based on the opportunities they each offer for repair and reuse through Additive Manufacturing.

In parallel to the site selection process, initial experiments are done using the machines available for prototyping at the *Laboratory for Additive Manufacturing in Architecture (LAMA)* of the TU Delft. This initial experimentation with the technology gives an idea of its constraints which is useful to expedite the later prototyping stage.

Upon identifying an opportunity for intervention, field research is done on the site, which is analyzed from a cultural and typological perspective. This includes architectural surveying, producing 3D scans of the damaged parts of the building, and interviewing experts to understand its history and cultural significance - and, ultimately, the needs inherent in its preservation.

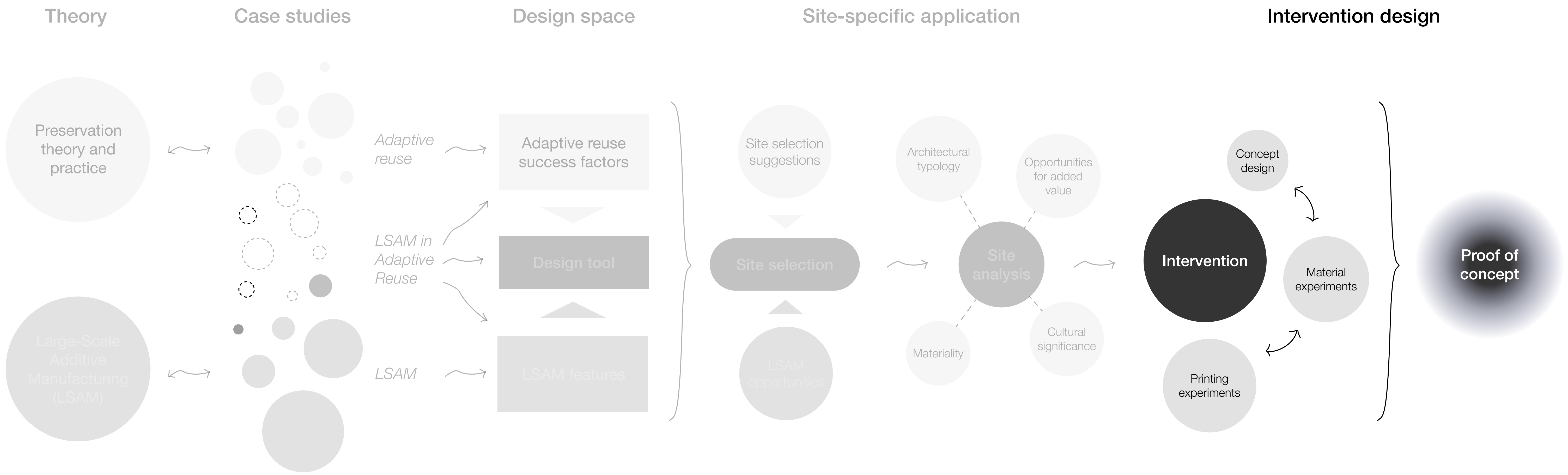


Intervention design

Finally, an intervention is designed following the opportunities identified with the help of our design tool and the intersection between said opportunities and the historical and architectural significance of the site.

First, a section of the building is identified as suitable for a 3D-printed intervention according to the conclusions of the site analysis. The intervention is then broken down into its key features, detailing how each attempts to balance the needs of the site with the opportunities proposed by the design tool. These features are expressed as the result of a series of design inputs extracted during the site analysis, with those of them that require validation through physical means being prototyped and evaluated at LAMA.

The final design constitutes a proof of concept in the form of a physical demonstrator that embodies all the aforementioned features, enabling the creation of additional value in a 3D-printed intervention.



Part II
Breaking down the disciplines

Identifying opportunities for value creation through literature

Preservation theory and practice

The background research attempts to answer the background questions postulated in the previous chapter. It is split into two main sections, each corresponding to the two disciplines combined in the project: Cultural Heritage preservation and Large-Scale Additive Manufacturing.

Cultural heritage

Preservation emerges as a response to threats to our collective Cultural Heritage; however, CH encapsulates a wide variety of concepts. Even tangible heritage is still not specific enough for the purposes of this project.

Though a unanimous definition of Cultural Heritage has never been universally agreed upon (Codarin, 2020), we can accept UNESCO's definition of it as described in the *1972 World Heritage convention*. In it, Cultural Heritage is described as:

- *"Monuments: architectural works, works of monumental sculpture and painting, elements or structures of an archaeological nature, inscriptions, cave dwellings and combinations of features, which are of outstanding universal value from the point of view of history, art or science;*
- *Groups of buildings: groups of separate or connected buildings which, because of their architecture, their homogeneity or their place in the landscape, are of outstanding universal value from the point of view of history, art or science.*
- *Sites: works of man or the combined works of nature and man, and areas including archaeological sites which are of outstanding universal value from the historical, aesthetic, ethnological or anthropological point of view." (UNESCO, 2023)*

Within this definition of CH, the present research focuses on architectural works - more specifically, heritage buildings at risk of degradation -, as well as sites, so long as they hold certain architectural value and are not archaeological sites (since the integration of LSAM in such a context could prove highly controversial).

When it comes to the conservation of said heritage, the Nara Conference on Authenticity defines it as *"all operations designed to understand a property, know its history and meaning, ensure its material safeguard, and, if required, its restoration and enhancement."* (Agency for Cultural Affairs, 1995). Understood as such, restoration and enhancement are an inherent part of CH conservation. However, there are a variety of approaches to this restoration and enhancement. This part of the research centers around that of **Adaptive Reuse**.

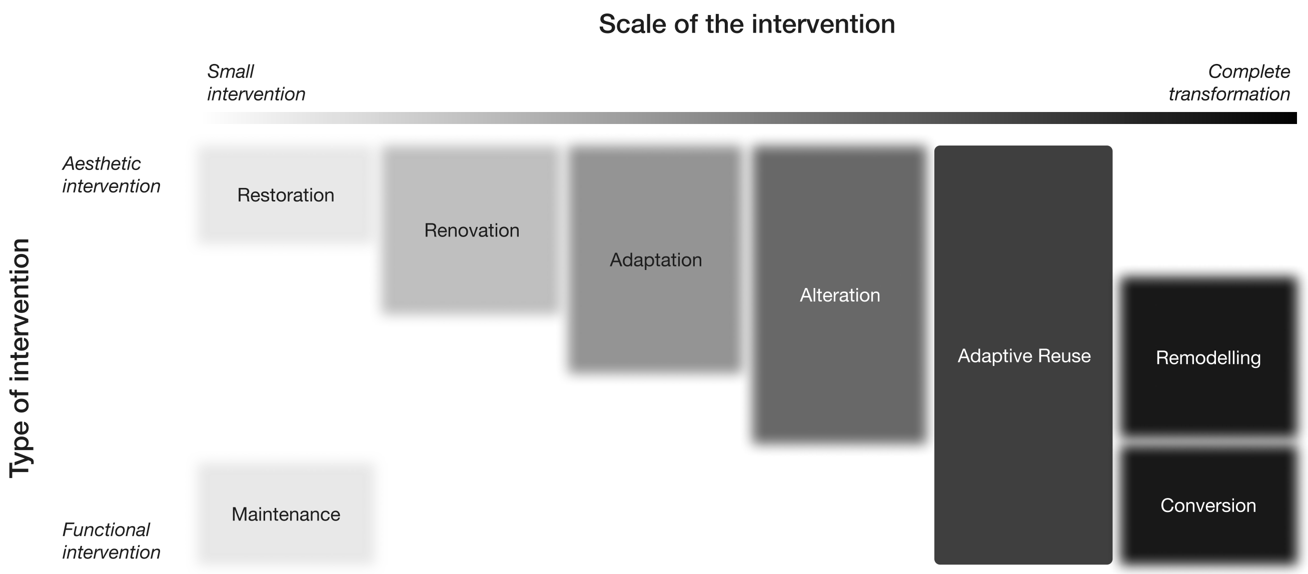
Restoration, adaptation, remodelling

The processes related to the conservation of heritage are incredibly complex and diverse, consisting of varying, often contradictory, approaches to preservation. Without going into an extensive discussion about the current definitions of conservation processes, the main terms used in the field are described here as succinctly as possible. It is necessary to have an understanding of these terms in order to position adaptive reuse as a discipline, and this research in particular, correctly among all other conservation practices.

Restoration and enhancement, as mentioned in the *Nara Conference on Authenticity* constitute very different interpretations of conservation. The *Burra Charter* describes restoration as *"returning a place to a known earlier state by removing accretions or by reassembling existing elements without the introduction of new material"* (ICOMOS, 2013). In essence, attempting to recover the original structure as authentically and with as little intervention as possible. In contrast to the rigidity of restoration, enhancement poses a more flexible approach to conservation that can be stretched to include changes to the building's functions or its aesthetic appearance, to an extent.

A variety of terms have been used to describe transformation or enhancement efforts in the built environment. Each describe specific processes that range from more continuity-focused maintenance works to works of complete transformation, with renovation on one end, and remodeling on the other (Plevolets & van Cleempoel, 2019). Renovation can be understood as the repair of a building to an acceptable condition (Douglas, 2006), while remodeling is characterized by the building's change in function (Brooker & Stone, 2004). As is illustrated in Figure 6, on the more conservative side of the spectrum we see restoration and maintenance as non-invasive aesthetic and functional interventions, respectively. On the more transformative side, conversion and remodeling.

Figure 6. Terms used to describe works of preservation, arranged according to the scale of the intervention and its focus, be it aesthetic or functional in nature.



Adaptive reuse is not quite a work of complete transformation, as it proposes changes that are both functional and aesthetic, yet still aims to preserve the historic character of the site, highlighting what is left of the original structure, as well as reusing materials and fostering a continuation of cultural phenomena through built infrastructure (Wong, 2017). Justine Clark accurately describes it as giving *"new life to a site, rather than seeking to freeze it at a particular moment in time, it explores the options that lie between the extremes of demolition or turning a site into a museum. Adding a new layer without erasing earlier layers, an adaptive reuse project becomes part of the long history of the site. It is another stage, not the final outcome"* (Clark & Wolkenberg, 2013).

Because of their inclusive approach to preservation and their envelopment of both functional and aesthetic reforms, adaptive reuse projects hold an excellent balance between creative freedom and the practical challenge of preserving as much of the building's original character as possible. However, it is important to understand the requirements of such a delicately balanced project. Though a lot of these will inevitably be site-specific – i.e., they will depend on the former and projected uses of the building, its environment, history, and so forth -, we can devise a set of general guidelines for tackling adaptive reuse works that can be useful to cross check not only when designing the intervention, but also when looking for a site upon which to intervene.

Success factors in Adaptive Reuse projects

In their work, Vafaie et al. (2023) provide an overview of the success factors of adaptive reuse projects in heritage buildings. What they call success factors is useful to this research in the formulation of preliminary requirements for adaptive reuse interventions using large-scale additive manufacturing, as well as in the identification of opportunities within the space. The reason for this being that the factors identified in their research are not defined as absolute necessities in adaptive reuse projects, but rather guidelines upon which to base the potential for success of such a project; depending on the site, some of these factors will be strict requirements, while some, opportunities for value creation.

In order to make these success factors intelligible and adapt them to the context of this project, they are condensed, rewritten, and clustered according to five categories:

"Adaptive Reuse success factors are not requirements or wishes - they signal opportunities for value creation"

Impact: Impact refers to the effect of the intervention on the original building fabric. It speaks to the permanence of interventions and their adaptability to future interventions and changes.

Form: Form relates to the aesthetic or formal impact of the intervention on the character of the building. It includes continuity and aesthetic consonance (or dissonance) as ways of bridging the building's past, present, and future.

Material: Material encapsulates the effect of materials on the outcome of the project. They range from environmental consequences, to formal and functional effects.

Sustainability: Community speaks to the social impact of the intervention; i.e., its effect on the building's future users, both direct and indirect.

Community: Sustainability gathers success factors that assess the environmental impact of the intervention, including energy efficiency, resource reuse, and promoting biodiversity.

Upon analyzing individual Adaptive Reuse cases (which are discussed in the following chapters report), it becomes clear that the uniqueness of these projects creates different requirements depending on the site, its history, and its projected new use. This means that none of these factors can be categorized as requirements or wishes. Instead, they are all opportunities for value creation. As such, they are all identified as Adaptive Reuse success factors, and are further divided into general success factors, and design-related success factors.

General: **General success factors** are achievable through intangible means. That is, they are dependent on the designer's approach to the intervention. For example, co-design is categorized as a general criterion because it pertains to the involvement of local communities in the design process, it is not directly influenceable by the technology used in the intervention.

Design: **Design-related success factors** are directly influenceable by Additive Manufacturing. These are the guidelines that will help identify opportunities for LSAM in the preservation space. For instance, natural light as a design criterion refers to the use of natural lighting solutions to minimize energy use in revamped buildings. This can be tackled through the printing of geometries that allow natural light to enter the building in specific ways.

These success factors are therefore not only useful when evaluating the success of an Adaptive Reuse project, but they serve as useful guidelines when searching for a site upon which to intervene, as they give an overview of the theoretical opportunities for LSAM in Adaptive Reuse. They are shown in the next spread, clustered and coded according to the categories described here.

Impact

Minimum intervention	Materials and elements that are considered inseparable from the historic character of the building are not intervened upon.
Reversibility	Interventions do not limit the potential for future re-adaptations of the building. They are reversible and/or removable.
Supporting alterations	Interventions support alterations for future reuse. They might not be removable, but they can be built upon.
Extending the building's life	Interventions extend the building's useful life.
Modularity	Interventions are made of modular elements that are not only removable for future reuse, but that make the building's use more dynamic.
Simultaneous repair and reuse	Satisfying both repair and reuse with multifunctional interventions.

Form

Recognizability	Alterations and additions to the building fabric are explicitly distinguishable from the original building.
Aesthetic harmony	Alterations and additions to the building fabric achieve architectural harmony and are visually compatible with the original building.
Technological innovation	Interventions use technologies that are consistent with current technical trends, making the intervention a reflection of the present time.
Perpetuating heritage	Interventions maintain the heritage and cultural significance of the building.
Layering	Highlighting the building's changes over time, both showing and contributing to the historic layering of interventions.
Bridging past and future	Providing continuity between the building's original use (and, therefore, its character) and its new one.
Continuity	Creating a new visual and formal language that seamlessly blends the tradition of the site with its new use in the present time.

Material

Material choice	Choosing materials on the basis of reversibility, durability, formal compatibility, and relevance to the site.
Material reuse	Reusing intact and undamaged construction materials and architectural elements.
Local materials	Using local building materials and renewable sources of energy.
Environmental impact	Considering environmental impact throughout the entire life cycle of the intervention.

Community

Urban regeneration and upgrading	Interventions acting as a catalyst for the urban upgrading of the surrounding areas.
Quality of life	Improving the quality of life of the building's future users.
Social cohesion	Generating social impact by promoting a feeling of belonging and a shared cultural identity enabled by the preservation of the building.
Co-design	Involving future users and residents of the area in the design and manufacturing process.

Sustainability

Natural light	Integrating natural lighting solutions in the repurposing of the building.
Airflow	Enabling better airflow between the different spaces in the building, as well as between the inside and outside.
Accessibility	Making the building more accessible for all types of people and all transport modes.

Impact

Climate adaptation	Crafting elements that solve problems related to climate adaptation through passive solar strategies.
Green spaces	Integrating open green spaces into the repaired sections of the building. Integrating nature, plants, and animals as new users of the building.

General factors

Design-related factors

Figure 7. Adaptive Reuse Success factors categorized.

Adaptive Reuse case studies

In the Adaptive Reuse case studies, projects were studied in their fulfillment of our previously identified AR success factors, as well as to form an understanding of how different architects have approached the problem of preservation according to the characteristics of a site. They served to understand exemplary approaches to AR and look for inspiration when designing the intervention at a later stage in the project.

Selection guidelines

The projects presented here were chosen based on the following guidelines:

- **Presence of ruins**. Adaptive reuse often involves adapting a historic building for reuse by designing and building on top of the existing building fabric. This happens in cases where there either is no damage, or the damage is solved almost independently from the intervention that facilitates the new use, i.e., repair and reuse are not achieved simultaneously. Because of the potential of 3D printing to fit into the digital workflow described in the *Problem definition* chapter, buildings with damaged fragments or volumetric losses are much more suitable for 3D-printed interventions than those without gaps in the building envelope (Codarin, 2020).
- **Special emphasis on preserving heritage**. Since Adaptive Reuse is very permissive, allowing a great deal of creative freedom, many projects dismiss the original character of the sites. They might use the preexisting building elements for economic or environmental reasons and, though these are valid reasons, they are not in line with the aim of this project.
- **Variety**. Different types of reuse give a more complete understanding of the potential of Adaptive Reuse and designers' approaches towards it. Certainly, there would be no point in including projects with no significant differences. Variety is considered in the materials used in the intervention, the type of damage present, the relationship between the building's former use and its new one, and the uses in themselves.

The case studies were extracted from books on Adaptive Reuse (Plevolets & van Cleempoel, 2019; Kuipers & de Jonge, 2017), papers on the adaptation of ruins (Codarin, 2020; Guidetti & Robiglio, 2021; Mısırlısoy & Günçe, 2016), and architecture websites with exemplary projects of ruin adaptation and reuse (Abe, 2022; Donaldson, 2024).

Case study index

Can Sau. Emergency Scene

by Un Parell 'Arquitectes

Location: Olot, Spain
Year of completion: 2019
Category: Adaptive Reuse

Project properties

Original materials: **Reinforced concrete**

Original use: **Ruins of an old building**

Problem: **Unused real estate, unpleasant atmosphere, deterioration of facade**

Intervention materials: **Brick, mortar, steel**

New use: **Urban stage (public space)**

Intervention: **Vaulted niches**

Durability of intervention: **Permanent**

Description

The demolition of an adjacent building in the center of Olot left three buttresses and part of a wall exposed. This project used the semi-enclosed gap created by these elements to build an urban stage that fit in with its surrounding architecture.

Discussion

The Can Sau project is a good example of an adaptive reuse project with "soft constructive" potential (Guidetti & Robiglio, 2021). This is because the small traces of ruins enable greater creative freedom in the project. However, it is still subject to restrictions from the surrounding architecture. In fact, this project is judged through its relation to the buildings around it rather than the ruins upon which it builds.

Therefore, the vaulted niches that are built as part of the intervention are designed as a public space. They feature openings that show the layering of interventions and connect the present structure to the past. The materials used, while not synchronous with the ruins, are inspired by an adjacent church, of which the Emergency Scene now functions as a public space.

Success factors covered

Minimum intervention	Technological innovation	Environmental impact
Reversibility	Perpetuating heritage	Urban regeneration and upgrading
Supporting alterations	Layering	Quality of life
Extending the building's life	Bridging past and future	Social cohesion
Modularity	Continuity	Co-design
Simultaneous repair and reuse	Material choice	Natural light
Recognizability	Material reuse	Airflow
Aesthetic harmony	Local materials	Accessibility
Climate adaptation	Green spaces	

References

Guidetti, E., & Robiglio, M. (2021).
The Transformative Potential of Ruins. A Tool for a Nonlinear Design Perspective in Adaptive Reuse. Sustainability.
All images and details sourced from:
Un Parell d'Arquitectes. (2019). Can Sau. Emergency Scene. Retrieved from Un Parell d'Arquitectes: https://www.unparelldarquitectes.cat/#can-sau-escenografia-de-urgencia/17

Figure 8. Exposed buttresses and partial wall.

Figure 9. Material layering showing the history of interventions.

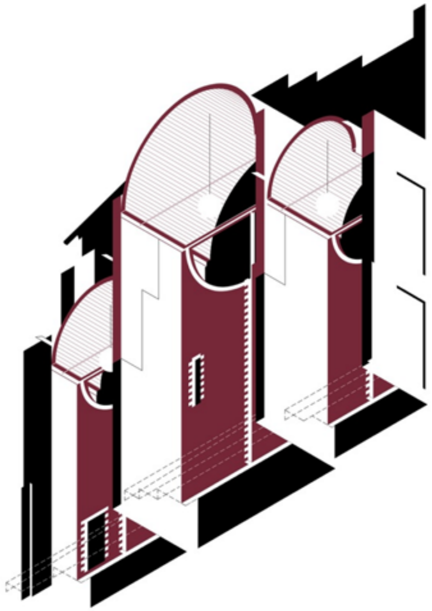


Figure 10. Intervention (red) fitting into preexisting architecture (black)

Figure 11. New use: open-air stage for public events

Figure 12. Details by inspired by the neighborhood's history

Escuelas Pías de San Fernando
by José Ignacio Linazasoro

Location: Madrid, Spain
Year of completion: 2004
Category: Adaptive Reuse

Project properties

Original materials: **Brick, mortar, stone**
Original use: **School chapel**
Problem: **Decay, neglect - large volumetric losses and gaps in the building envelope**

Intervention materials: **Wood, metal, brick**
New use: **Offices, library, auditoriums**
Intervention: **New building, framing of ruins**
Durability of intervention: **Permanent**

Description

Forty years after the San Fernando School was bombed during the Spanish Civil war, the ruins of its chapel were transformed into a multifunctional building. The project is part of a rehabilitation project in the neighborhood of Lavapiés, Madrid.

Discussion

The ruins left behind by multiple catastrophes and years of decay were unrestorable to their original state. Thus, the reuse effort carried out here treated the ruins as the original structure, using their new structural properties to build modern facilities. For instance, a false vaulted ceiling was constructed much lower than the original ceiling, so the architects could use the original walls as support, instead of building additional elements.

Part of facilities built were planned outside of the original floorplan, and the entire project was designed with and around the ruins, using them creatively rather than restrictively. Old fragments were arranged and framed with bricks in the new facade highlighting their nature as ruins and fragments of the past.

Success factors covered

Minimum intervention	Technological innovation	Environmental impact
Reversibility	Perpetuating heritage	Urban regeneration and upgrading
Supporting alterations	Layering	Quality of life
Extending the building's life	Bridging past and future	Social cohesion
Modularity	Continuity	Co-design
Simultaneous repair and reuse	Material choice	Natural light
Recognizability	Material reuse	Airflow
Aesthetic harmony	Local materials	Accessibility
Climate adaptation	Green spaces	

References

Images and details sourced from:
Linazasoro, J. I. (2016). Centro cultural Escuelas Pías de Lavapiés. Retrieved from HIC Arquitectura: https://hicarquitectura.com/2016/06/jose-ignacio-linazasoro-centro-cultural-escuelas-pias-de-lavapies/
Gómez, M. (2012). Escuelas Pías de San Fernando. Retrieved from Arte en Madrid: https://artedemadrid.wordpress.com/2012/07/08/escuelas-pias-de-san-fernando/


Figure 13. Old fragments framed in the brick facade.

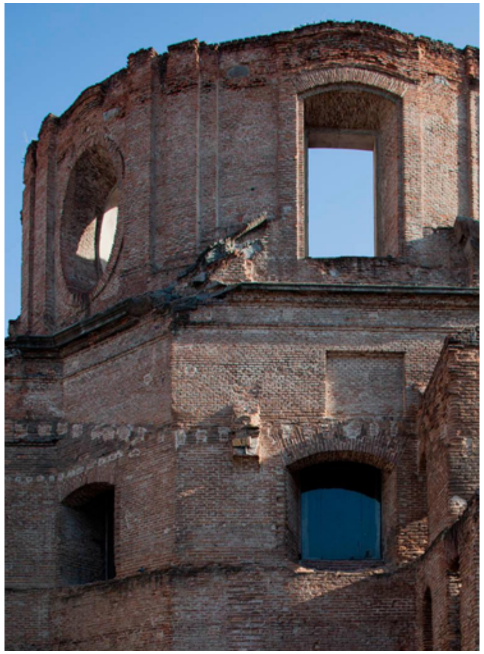


Figure 14. Reconditioned chapel ruins from outside.

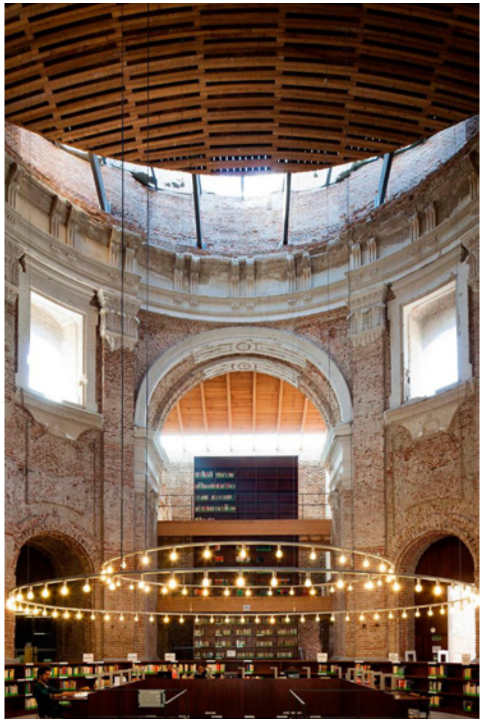


Figure 15. False ceiling on the inside of the chapel (now a library).

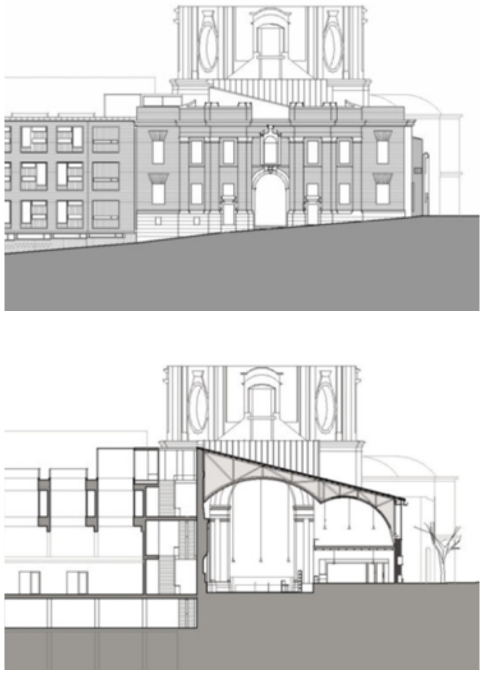


Figure 16. Facade and section drawings showing the relationship between the ruins and the intervention.

Kolumba Art Museum

by Peter Zumthor

Location: Cologne, Germany
Year of completion: 2007
Category: Adaptive Reuse

Project properties

Original materials: **Stone**

Original use: **Church**

Problem: **Bombings - large volumetric losses and damaged building fragments**

Intervention materials: **Brick, mortar**

New use: **Museum**

Intervention: **New building, framing of ruins**

Durability of intervention: **Permanent**

Description

The museum is built on the ruins of the Church of St. Columba, which was destroyed in WW2 bombings. It also features Roman and medieval ruins, all of which the architect unified using a single, meticulously-chosen building element.

Discussion

This adaptive reuse project is especially significant because of its materiality. The variety of ruins discovered on the site meant that a modern intervention would have to find a way to embrace multiple architectural styles and meanings. The museum was built on a site that had been built and rebuilt multiple times. This made the historical layering of the interventions so intense that it became the centerpiece of the new museum.

Peter Zumthor chose a single architectural element to dialogue with the ruins: a handcrafted, unusually long, grey brick designed specifically for this project. The size and color of the bricks strongly affect the materiality of the building. They are an excellent example of how a single architectural element can carry the weight of an entire preservation project.

Success factors covered

Minimum intervention	Technological innovation	Environmental impact
Reversibility	Perpetuating heritage	Urban regeneration and upgrading
Supporting alterations	Layering	Quality of life
Extending the building's life	Bridging past and future	Social cohesion
Modularity	Continuity	Co-design
Simultaneous repair and reuse	Material choice	Natural light
Recognizability	Material reuse	Airflow
Aesthetic harmony	Local materials	Accessibility
Climate adaptation	Green spaces	

References

Details sourced from:
Plevolets, B., & van Cleempoel, K. (2019). Adaptive Reuse of the Built Heritage: Concepts and Cases of an Emerging Discipline. Routledge.
Images sourced from:
Zumthor, P. (2008). KOLUMBA. Retrieved from Kolumba Art Museum of the Archdiocese of Cologne: https://www.kolumba.de/?language=eng&cat_select=1&category=14&artikle=61

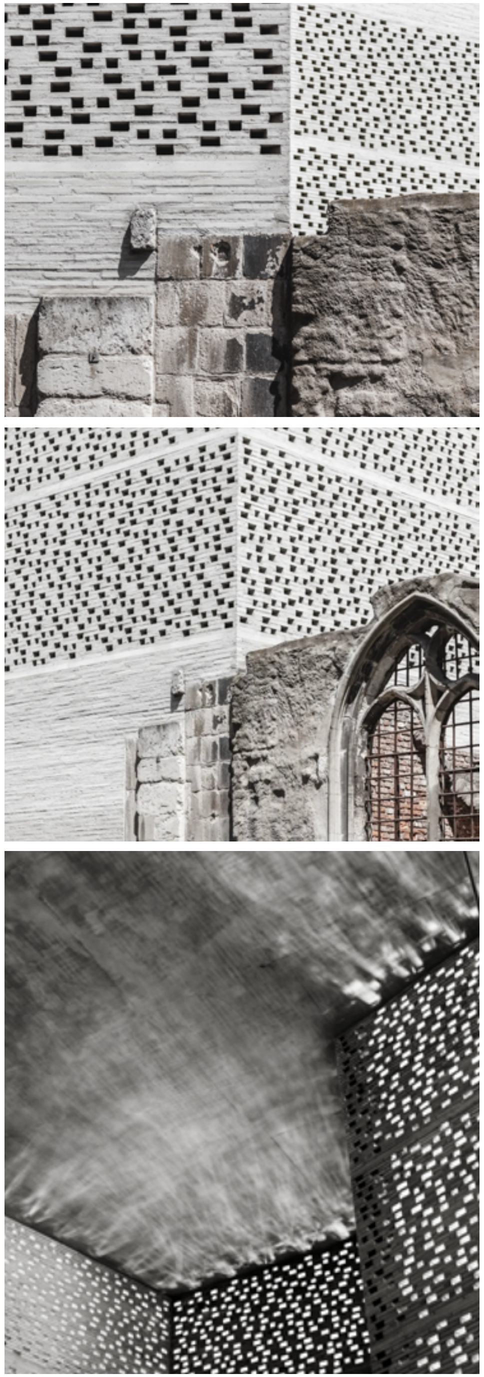


Figure 18. Bricks framing the architectural ruins. The perforations on the facade bring a diffuse natural light into the building that changes throughout the seasons.

Figure 17. The ruin hall. Underneath the ruins of the church, Roman and medieval ruins were discovered. Thin metal columns support the colossal space which is lit up dramatically by the diffuse light coming in through the porous facade. The bricks dialog with the ruins both directly and indirectly, through light and shadow.

Figure 19. Facade and section drawings showing the relationship between the ruins and the intervention.

Matrera Castle
by Carquero Arquitectura

Location: Cádiz, Spain
Year of completion: 2011
Category: Adaptive Reuse

Project properties

Original materials: **Stone, mortar**
Original use: **Fortress**
Problem: **Decay - volumetric losses, fallen and lost fragments, wall gaps**

Intervention materials: **Concrete**
New use: **Restored fortress**
Intervention: **Restored volume, framed ruins**
Durability of intervention: **Permanent**

Description

The restoration of the Matrera Castle is born out of a law imposed by Spanish preservation authorities that prohibits mimetic reconstructions. It attempts to restore the original architectural volume of the fortress with reinterpreted materials.

Discussion

What is interesting about this project is the translation of restoration methods used in art restoration, where the importance of recovering the volume of the original artefact warrants a reconstruction of it around the original fragments. For this purpose, the new building fabric must be as minimalistic as possible, highlighting the the preserved structure while allowing visitors to imagine how the original monument must have been. It makes no interpretations or bold attempts at reimagining the building's character (even though it eventually does severely affect its restored materiality).

In contrast with the other projects analyzed here, the aim of this preservation effort is not to give an image of the future, but rather to evoke the past.

Success factors covered

Minimum intervention	Technological innovation	Environmental impact
Reversibility	Perpetuating heritage	Urban regeneration and upgrading
Supporting alterations	Layering	Quality of life
Extending the building's life	Bridging past and future	Social cohesion
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Images sourced from:
Zumthor, P. (2008). KOLUMBA. Retrieved from Kolumba Art Museum of the Archdiocese of Cologne: https://www.kolumba.de/?language=eng&cat_select=1&category=14&artikle=61

Figure 20. Restored tower in context.

Figure 22. Drawings showing the original fragments and the volumetric restoration of the tower.

Figure 21. Translation of reparation techniques used in art restoration to monument restoration.

Tainan Spring
by MVRDV Architects

Location: Tainan, Taiwan
Year of completion: 2020
Category: Adaptive Reuse

Project properties

Original materials: **Reinforced concrete**
Original use: **Shopping mall**
Problem: **Demolition due to decreased use, leaving behind unused real estate**

Intervention materials: **Concrete**
New use: **Public park**
Intervention: **Urban pool and greenery**
Durability of intervention: **Permanent**

Description

Tainan Spring is an adaptive reuse project carried out in the ruins of a former shopping mall. It works towards the sustainable transformation of the city of Tainan while revealing layers of its past, making the transition visible.

Discussion

The ruins incorporated in the project are purposefully left behind after the demolition of the shopping mall, referencing a Roman forum and offering a visual marker of the history of the city, which transitioned from a marine and fishing industry to one of leisure and consumption. Now, it is transitioning again to a circular economy - a city with less traffic and more greenery, which in Tainan Spring literally grows out of the remnants of its industrial past.In contrast with the other projects analyzed here, the aim of this preservation effort is not to give an image of the future, but rather to evoke the past.

Here, the past is preserved more as a historical record rather than an art piece, offering a different interpretation of adaptive reuse. Monuments and buildings of the past must not only be preserved because of their artistic value, but rather because they are a part of the city's history - its rights as well as wrongs. Rather than erasing the past, it is proudly shown as a testament to the progress made in the revitalization of the city and its values.

Success factors covered


Figure 23. Tainan Spring in the recessed former parking garage of a mall, shielded from traffic noise.


Figure 24. The square in the context of a larger urban regeneration project that adds more green spaces to the citiscape. art restoration to monument restoration.


Figure 25. Playground with concrete frame and follies for shops and kiosks in the background.


Figure 26. Recessed urban oasis in context.

References

All images and details sourced from:
MVRDV Architects. (2020). Tainan Spring. Retrieved from MVRDV: https://www.mvrdv.com/projects/272/tainan-spring

Conclusions on the Adaptive Reuse Case Studies

The five cases analyzed show very different examples of Adaptive Reuse, showcasing just how diverse preservation approaches really are. This seems to be mainly because each building, monument, or ruin defines the boundaries within which the architect can operate. Still, these are not strict boundaries - the same ruins can be interpreted in different ways by different people, and when combined with their future use, they prove more enabling than restrictive. That is, the new use asks for an intervention and the ruins determine how the intervention is to be carried out, leaving it up to the designer to achieve a balance between restoration and reuse.

None of the projects analyzed (and, upon glancing over other projects during the selection process, no Adaptive Reuse projects in general) were seen to fulfill all of the design-related success factors. This is only natural, as the focus of the intervention cannot encompass everything at the same time and is largely informed by the needs of the site and its proposed use, let alone the monetary, planning, and logistic limitations of the project.

“The new use asks for an intervention and the ruins determine how the intervention is to be carried out, leaving it up to the designer to achieve a balance between restoration and reuse.”

Across the five cases, some had a unique approach to preservation, focusing on framing the ruins in a sort of display. The ruins in San Fernando, Kolumba , and Matrera are treated as centerpieces in the final design. The interventions function as scaffolding, framing the ruins and highlighting their importance. In San Fernando, the intervention is almost completely separate from the ruins. The original building functions as a shell, encasing the revamped interior. The roof is not rebuilt and the wall gaps in the facade are a testament to the origins of the damage – the Spanish civil war. They are left intact and repaired with glass. In this case, the cause of deterioration is as important as the monument itself – an integral part of its history.

Figure 27. Ruins in San Fernando encased in brick on the facade of the new building.

Fragments of columns and arches are framed with red brick in the new façade, just like Zumthor does in Cologne, where the variety of the ruins begs for a minimalistic intervention. Here, various historic periods coexist; therefore, the intervention must dialogue with them without attracting too much attention. The bricks used in the façade of the museum bring in diffuse light that spotlights the ruins on the inside, while physically framing them on the outside. The intervention is almost a stage where the ruins reign supreme and the building becomes a museum in itself, encasing works of art in the actual building fabric. Finally, the intervention in the Matrera Castle is almost too respectful of the ruins; to the extent that it borrows a technique from artefact restoration, quite literally filling in the gaps with concrete and attracting as little attention as possible.

Figure 28. Ruins in Kolumba. A variety of time periods bound together with a minimalistic unifying element: gray brick.

In the cases of Can Sau and Tainan Spring, the ruins do not have a particular cultural significance, and are used as design elements that give the project an interesting edge. They still preserve the heritage of the site, as this was one of the selection guidelines, yet they are used more creatively. In the case of Can Sau, the ruins did not fit in with the surrounding architecture and, in turn, the intervention highlights the heritage of the neighborhood, instead of that of the ruins; in Tainan Spring, they are used as a storytelling device, showing the city’s past and present coexisting, a testament to the evolution and transition of the city from industrial hub to green metropolis. Tainan Spring and Can Sau also serve as excellent examples of how an Adaptive Reuse project can foster social cohesion; the former by connecting Tainan’s citizens through their common history, and the latter more directly, by creating a public space that both physically and metaphorically brings the neighborhood together.

“Ruins can also be used as storytelling devices where they do not hold museum value, highlighting the site’s past and connecting it to its present use.”

In a way, the constraints enforced by the heritage of the sites and their new uses enable creativity. This is to be expected, as open-ended problems often require the creation of new constraints to facilitate problem construction (Tromp, 2024). This is important to remember for the site-finding phase of the project, as sites without a proposed new use or restrictive building elements can make it more difficult to come up with an intervention; meaning that further restrictions need to be imposed on the project in order to facilitate the design of an intervention.

Figure 29. Ruins in Can Sau have no special significance. They are preserved simply because they cannot be removed. Thus, the heritage focus shifts to the neighborhood as a unit.

Lastly, it is interesting to note that none of these projects take into account the possibility of future alterations. None of them are removable or have been designed to accommodate subsequent adaptations of the buildings, almost as if they consider their interventions to be the last. That being said, all interventions in the history of a building appear to do this, perhaps because a removable intervention could give the impression of the project being temporary. In any event, this creates a repeating intervention cycle. Over time, architects in charge of preservation projects build and rebuild focusing on durability, not realizing that, at some point, damage will unavoidably occur and the problem will emerge even more restrictively than before.

Large-Scale Additive Manufacturing

This chapter will briefly describe the design and manufacturing process of Large-Scale AM. It includes all the essential knowledge needed to understand this process – its limitations and opportunities - and its potential for heritage preservation and enhancement.

Due to the limits imposed by the facilities available at the Laboratory for Additive Manufacturing in Architecture, Liquid Deposition Modelling (LDM) with clay will be used in this research to validate a hypothetical workflow and inform a proof of concept for the use of LSAM in adaptive reuse. The theoretical framework for the project, however, will consider Large-Scale AM independent of material.

Workflow

Additive Manufacturing, also known as 3D printing, uses Computer-Aided Design (CAD) to produce objects in a layer-by-layer fashion. That is, a number of two-dimensional layers are extruded and stacked on top of each other to create a three-dimensional geometry.

Although there is no official definition of what constitutes Large-Scale AM specifically, it can be understood as a more industrial and less commercialized way of producing 3D-printed pieces that are larger than those that commercial desktop printers can produce (CEAD, 2024). This lack of standardization means that LSAM printers are typically more customizable and adaptable to different printing environments and requirements, albeit less reliable, as they require a higher degree of expertise to be operated.

Equipment

The machine used in the study is the WASP 4010LDM printer. This machine works with a clay extruder and tank. It uses compressed air to push material into the extruder and an Archimedes screw to extrude it out of the nozzle. Therefore, despite it being in a vacuum-sealed system, it makes printing with cementitious materials difficult, as these need to be agitated continuously to prevent them from setting. In industry, concrete, mortar, and similar materials are printed with a system that uses a mixer connected to a pump which continuously extrudes material.

WASP 4010 LDM

Type of printer	DELTA
Coordinate system	Cartesian
Maximum print height	1m
Start/stop	YES
Variable layer height	YES
Non-planar printing	NO
Compatible with slicing software	Commercial
Compatible with file types	.gcode
Tank capacity	5 litres
Available material	Stoneware clay

Figure 30. WASP 4010 LDM Printer Specifications. Image sourced from https://www.3dwasp.com/en/ceramic-3d-printer-wasp-40100-ldm/

Slicing, printing, and design

Slicing is the process of converting CAD-generated models into printing instructions for the printer. It involves breaking down the object into the layers that make up the print and sending this information in the form of a Computer Numeric Control (CNC) code to the printer (Carolo, 2024). The CNC code used by 3D printers is called G-code and, though it uses slightly different grammar depending on the printer, it generally includes point coordinates, speeds, extrusion rates, waiting times, and more.

Commercial desktop printers use specialized slicing programs that automate the slicing process, allowing the user to control the parameters involved in the print – layer height, extrusion rate, speed, infill, etvvc. In LSAM, however, the slicing process is often not automated, and in many cases, a slicer has to be built for each specific machine. The machine's limitations therefore inform the design and slicing of the objects it produces. In the case of the WASP, the printer has very similar capabilities to a desktop printer, as it is compatible with third-party slicers. However, more precise control of the toolpaths, machine speeds, and extrusion rates can only be achieved through algorithmic design software such as Grasshopper, as it allows for the printing path to be created and edited directly in the modelling software.

When printing at a large scale, the layers of a 3D-printed object become highly visible and start to influence the look and feel, as well as the mechanical behavior of the object much more noticeably. Normal slicing software works by intersecting the digital objects with planes that are parallel to the build platform or printbed (Figure 31), with the distance between those planes being the specified object's layer height (Pelzer & Hopmann, 2021). Using Grasshopper to generate geometries with varying layer heights, the WASP becomes capable of non-planar printing. This can be used to affect the object's aesthetics and mechanical performance, but also allows for printing onto existing objects with curved surfaces.

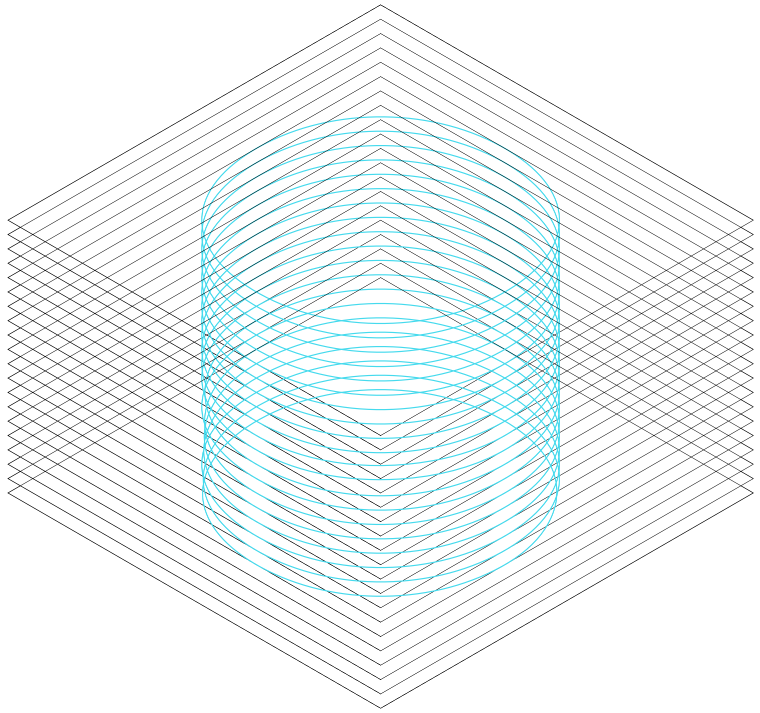

Figure 31. Slicing of a 3D object by intersecting it with horizontal planes

Figure 32. Printing onto objects with curved surfaces. Visual adapted from Pelzer & Hopmann (2021)

Material

The material available for printing at LAMA is stoneware clay, a material with excellent properties for laboratory testing. It is versatile, cheap, and – if not fired - can be rehydrated and recycled for reprinting. Furthermore, it has been used as a reference material in a variety of studies (Codarin, 2020; Peters, 2012; Xu & Huang, 2020; Friedman, Kim, & Mesa, 2014).

Figure 33. Stoneware clay for 3D printing available for prototyping at LAMA.

LSAM Case Studies

The theory behind Large-Scale Additive Manufacturing as a production method provides a basis for understanding the case studies, their complexity, and their use of 3D printing principles in the creation of features that make them stand out among other manufacturing processes.

While in Adaptive Reuse, case studies were used mostly as inspiration and to understand current preservation practices. Here, they are used to extract features enabled by 3D printing principles. Because these features are unique to 3D printing, the opportunities they offer are enabled by the technology, and any additional value derived from them will be owed to the power of AM as a production technique.

Selection guidelines

LSAM cases were chosen based on the following guidelines:

- **Integration of features**. The aim of the case studies is to explore how LSAM can add value to a design project in ways that are enabled by the nature of the technology itself. Projects are therefore chosen based on how they use 3D printing principles to integrate features into the design of printed objects. This helps find projects with characteristics that are unachievable with other technologies, and therefore enable us to extract opportunities for value creation specifically through 3D-printed means.
- **Material**. Projects were chosen that used LDM or FDM, as well as paste-like materials. Since the project focuses on the printing of clay, concrete, mortar, and materials with similar behaviors, other ones like plastic or metal were left out of the search – unless, that is, the principles used in the project could be applied to clay printing.
- **Printing location**. A variety of on-site and off-site printing projects were used to understand the differences between both and their potential depending on the location of the intervention, the type of material used, and its post-processing.
- **Technology**. In some cases, the type of machine severely impacts the feasibility of the project. For this reason, SCARA, gantry, delta, and robotic arm systems were all represented in the case studies. This helped understand whether the technology choice was done on the basis of design requirements or on the availability of one machine or other in the production facility where the project was carried out.

The LSAM case studies were found by browsing architecture magazines (RuMoer, 2023; RuMoer, 2024), journal articles on Additive Manufacturing (Wolf, Laurens Rosendahl, & Knaack, 2022), student theses (Codarin, 2020; Jonnalagedda, 2023; Sridhara, 2022), the work of design and research studios focusing on digital fabrication (Gramazio Kohler Research & ETH Zurich, 2021; Studio RAP, 2019; Ochoa, Grading Light, 2021; Ochoa, Clarcke-Hicks, & Correa, Static Shift, 2023) and booklets from the annual symposium of Additive Manufacturing in the Built Environment (BE-AM, 2023; BE-AM, 2022; BE-AM, 2021; BE-AM, 2020; BE-AM, 2019).

- **Post-processing**. Not all interventions can be made in a fully automated environment. In fact, some materials require post-processing that impacts both the design and manufacturing process, as well as the materiality of the objects produced. Projects are better contextualized when the entire process is understood, rather than focusing only on the printing part of it.
- **Scale**. Different scales require different design considerations, machines, and project management. Large-Scale AM ranges from products to entire buildings, and the logistics at both ends of the spectrum are entirely different. Projects were chosen with varying scales, understanding the approaches designers have used to tackle works of all sizes.
- **Support**. While some printed pieces are freestanding, others need to be supported by external elements. Depending on the material used and the final assembly of the object, it might need additional supports.
- **Application**. To showcase the versatility of LSAM and take inspiration from a range of different uses, every project has a different application.
- **Technology Readiness Level (TRL)**. TRLs help gauge the feasibility and replicability of the results of a project. Some of the ones included are scaled prototypes in research environments, and some are commercial projects. Borrowing insights from either end of the spectrum will affect the TRL of the intervention to be designed in this project.

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Figure 34. Light diffusion through extrusion variability (left) and through toolpath variability (right).

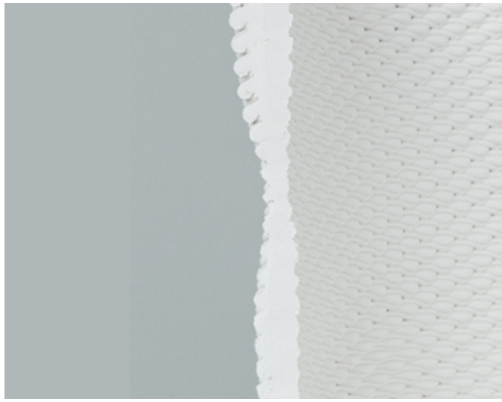


Figure 35. Variable extrusion cross-section

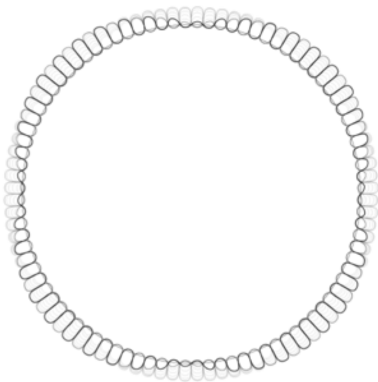


Figure 36. Variable extrusion toolpath top view

Figure 37. Variable toolpath cross-section

Figure 38. Variable toolpath top view

Grading Light

by Isabel Ochoa

Location: Waterloo, Canada
Year of completion: 2021
Category: Large-Scale Additive Manufacturing

Project properties

Material: **Clay (stoneware, porcelain)**

Technology: **SCARA printer**

Scale: **Product**

Application: **Lamp screens**

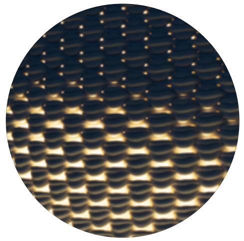
Printing location: **Off-site**

Post-processing of prints: **Bisque, glazing**

Support: **Freestanding, wall/ceiling-mounted**

TRL: **6**

Features



light scattering

Key principles

- Porosity.
- Variable Layer width.

Description

Grading Light studies the effects of light transmission and scattering through ceramic objects by taking advantage of porcelain's translucency properties, as well as generating porosity through toolpath variability.

Discussion

Grading Light provides an excellent example of the possibilities enabled by LDM printing in the creation of integrated features. Porcelain is known to be highly translucent after firing; this means that thinner walls in a porcelain object will allow more light to pass through. 3D printing enables parametric control of these thinner sections by controlling how much material the printer extrudes in specific areas. At the same time, changing the toolpath in a layer-by-layer fashion enables both the creation of openings in the geometry (for light passthrough), as well as thinner and thicker sections, this time through material stacking.

References

All images and details sourced from:
Ochoa, I. (2021). Grading Light: Utilizing plastic deformation to functionally grade ceramic light screens. University of Waterloo.

Figure 39. Detail of step mounting.

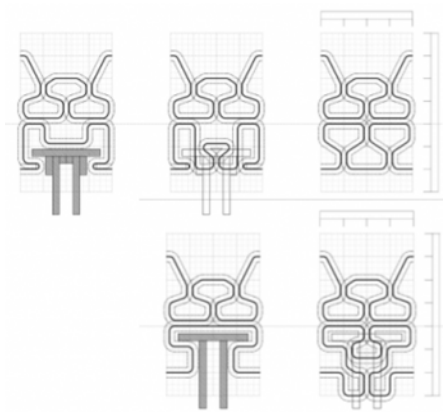


Figure 40. Top view section drawing of step mounting.

Figure 41. Variable infill density in printed object.

Figure 42. Detail of step fitting in with 3DP staircase.

Figure 44. Full view of 1:1 printed staircase.

Figure 43. Top view of variable infill density.

Architecture Continuity: From Materiality to Environment

by IaaC

Location: Barcelona, Spain
Year of completion: 2019
Category: Large-Scale Additive Manufacturing

Project properties

Material: **Adobe (raw clay)**

Technology: **Delta printer**

Scale: **Architectural**

Application: **Wall section**

Printing location: **Off-site**

Post-processing of prints: **None**

Support: **Freestanding**

TRL: **4**

Features

integrated support elements

gradient material properties

Key principles

- Parametric geometry control.
- Variable infill density.

Description

This graduation project exemplifies how 3D-printed structures can be designed and printed around physical, non-printed elements. Additionally, it shows how parametric design can be easily used to shift the center of gravity of printed geometries.

Discussion

In Architecture Continuity, we see a 3D-printed wall integrate mounting supports for a wooden staircase. Part of a larger project that also includes an arch opening and walls with integrated wooden beams, it showcases the potential of additive manufacturing in architecture in that it combines digital fabrication with traditional building techniques and elements. The computational design that enables the printing of the wall also provides control over its mechanical behavior. It allows the designers to predict printable and non-printable geometries, as well as the structure's center of mass, to make sure it can stand on its own. The wall itself is printed in one 40cm-tick piece, using a varying infill to give it better structural integrity. The infill itself is made denser or lighter in strategic areas to balance the weight of the whole structure.

References

All images and details sourced from:
Dubor, A., Cabay, E., Melchor, J., Chadha, K., Bettuchi, E., Riaz, S., Akbari, A., Chang, Y., Cengiz, O., Chen, Y., Datta, I., Du, Y., Foroughi, A., Kriki, P., Liao, Y.F., Loonawat, B.V., Randeria, S.C., Nejad, P.S., Tabassum, N. (2019) Architecture Continuity: From Materiality to Environment. IaaC.

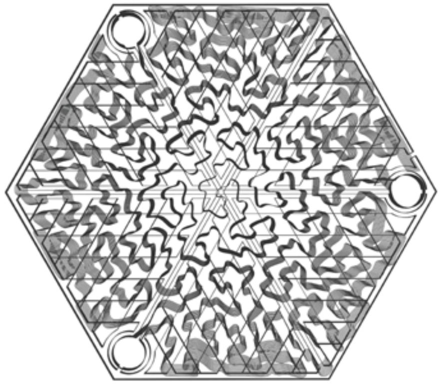


Figure 45. Panel toolpath.

Figure 48. Panels with planted coral samples.

Figure 47. Panel assembly in a factory environment.

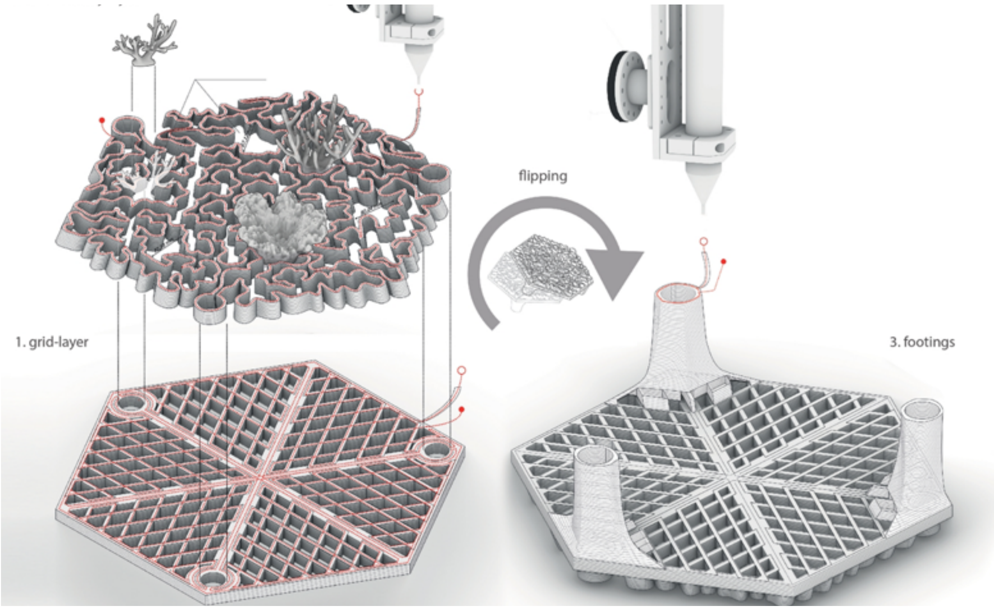


Figure 46. Printing process of base layer, bio-mimicry layer, and footings.

Reformative Coral Habitats

by the University of Hong Kong

Location: Hong Kong
Year of completion: 2020
Category: Large-Scale Additive Manufacturing

Project properties

Material: **Clay**

Technology: **6-axis robotic arm**

Scale: **Product**

Application: **Coral reef tiles**

Printing location: **Off-site**

Post-processing of prints: **Bisque firing**

Support: **Mounted on weight plates**

TRL: **6**

Features

biomimicry

Key principles

- Complex geometry control.

Description

Reformative Coral Habitats harnesses the potential of Additive Manufacturing to create complex geometries that simulate those of coral reefs, encouraging coral regrowth and preventing their detachment from the structure.

Discussion

In the project, 32 bespoke panels were printed, all with slightly different patterns, as the researchers wanted to assess their potential for growing coral. Algorithmic design and 3D printing enabled them to adapt the panels to the environmental conditions of the area where they were deployed, printing them with different dimensions according to their position on the ocean floor. Additionally, the geometries they chose were optimized for sedimentation passthrough as well as coral growth.

While coral regeneration does not directly relate to any architectural features, it showcases the ability of LSAM to produce bioreceptive structures that promote biodiversity, which does have implications in the built environment.

References

All images and details sourced from:
Lange, J., Ratoi, L., Lim, D., Hu, J., Baker, D., Yu, V., & Thompson, P. (2020). Reformative Coral Habitats. ACADIA 2020, 164-169.

Robotic Restoration

by Sara Codarin

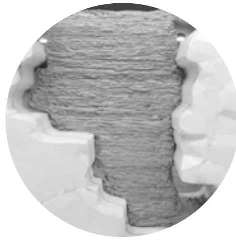
Location: Detroit, Michigan
Year of completion: 2020
Category: Large-Scale Additive Manufacturing for Repair

Project properties

Material: **Clay**
Technology: **6-axis robotic arm**
Scale: **Architectural**
Application: **Monument restoration**

Printing location: **On-site (simulated)**
Post-processing of prints: **None**
Support: **None**
TRL: **3-4**

Features



repair

Key principles

- Toolpath mapping onto 3D-scanned objects.

Description

Robotic Restoration proposes a digital workflow in the repair of volumetric losses in buildings using LSAM. It is the result of a PhD thesis exploring the potential of Additive Manufacturing in the conservation of heritage.

Discussion

This research project shows promise for the on-site printing of large lost building fragments. The repair toolpath is generated directly from a 3D scan of the damaged fragment and adjusted to the limitations of the robot. However, the project showed a lot of the problems of robotic on-site printing, such as:

- The collapse of layers under the weight of large amounts of material (given the size of the wall gap).
- The reach of the robot arm into every crevice of the gap and the parametrization of calculating 6th axis orientation so as to avoid collisions with the wall.
- Print resolution (due to the equipment used in the study).

References

All images and details sourced from:
Codarin, S. (2020). Innovative construction systems within building processes. An approach to large-scale robotic Additive Layer Manufacturing for the Conservation of Cultural Heritage. Ferrara, Italy: University of Ferrara.

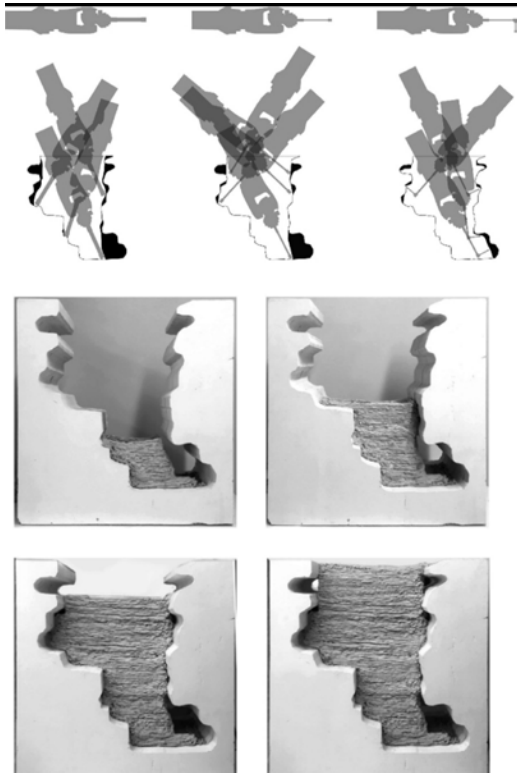
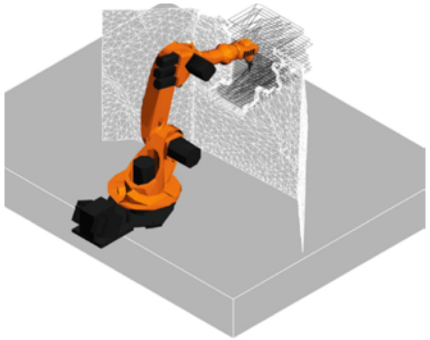


Figure 51. Tool orientation and layer-by layer printing of the fragment.

Figure 50. Panel assembly in a factory environment.



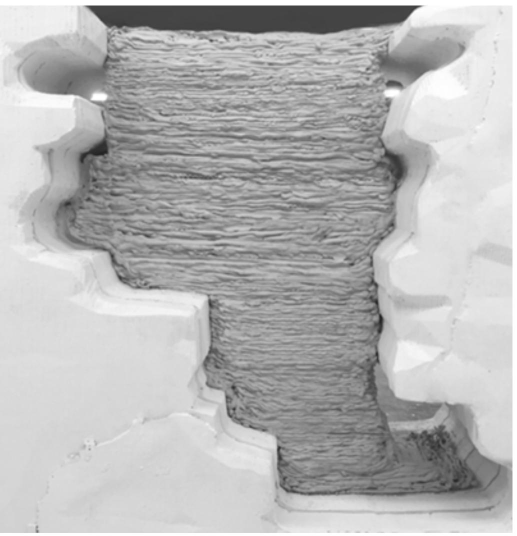


Figure 49. Repaired wall gap prototype.

Figure 52. Laboratory printing setup.

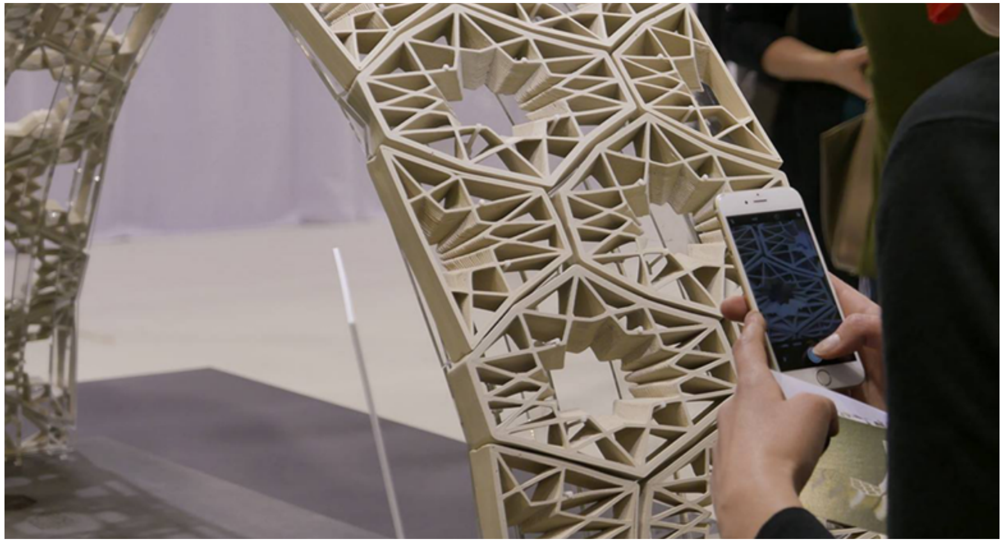


Figure 54. 1:2 scale prototype in exhibition.

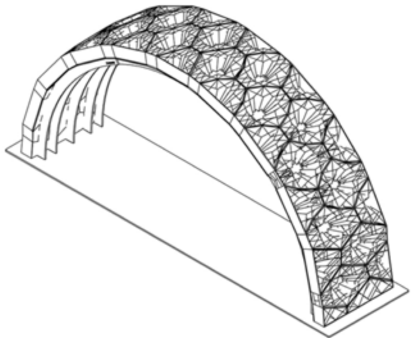


Figure 55. Schematic drawing of the vault.

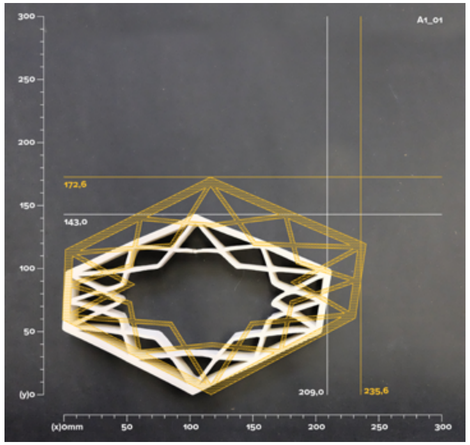


Figure 53. Non-uniform shrinkage of pieces after firing.

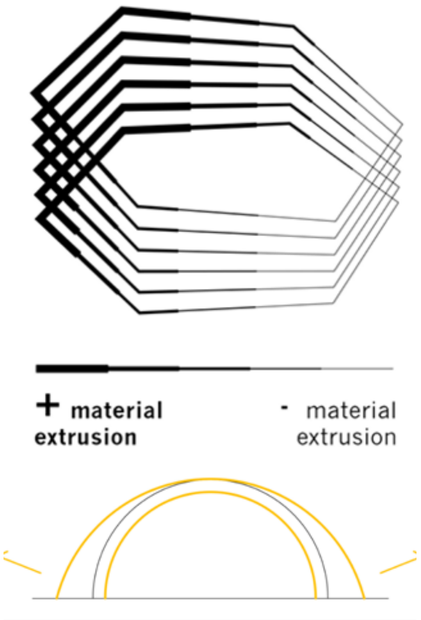


Figure 56. Variable layer height printing of elements to create a vaulted surface.

Free-form Ceramic Vault System

by João Carvalho, Bruno Figueiredo, and Paulo Cruz

Location: Braga, Portugal
Year of completion: 2023
Category: Large-Scale Additive Manufacturing

Project properties

Material: **Clay**

Technology: **SCARA printer**

Scale: **Architectural**

Application: **Shading vault**

Printing location: **Off-site**

Post-processing of prints: **Bisque firing**

Support: **Acrylic structure**

TRL: **3**

Features

shading

Key principles

- Parametric geometry control.
- Porosity.
- Variable layer height.

Description

Hexashade uses parametric modelling to design and print a series of interlocking ceramic bricks that provide shade based on the position of the sun in a specific geographic location.

Discussion

This project harnesses the power of 3D printing through the production of lightweight, porous structural elements that provide passive cooling to a building. Parametric design is used in determining the optimal shape of the bricks based on the position of the sun at the hottest time of day, as well as designing a (meant-to-be) self-supporting arch.

It also shows the limitations in ceramic modelling as the bricks printed shrunk in unpredictable ways upon being fired. This mismatch between digital and physical object meant that they did not interlock as predicted and ultimately required a supporting structure for their assembly. Still, the project exemplifies the potential of porosity in 3D printing for architectural uses, as well as variable layer heights for the creation of curved surfaces.

References

All images and details sourced from:
Carvalho, J., Figueiredo, B., & Cruz, P. (2023). Free-form Ceramic VaultSystem. Proceedings of the 37th eCAADe and the 23th SIGraDi Conferences (pp. 485-492). Porto: eCAADe.

Figure 58. Infill geometries optimized for air flow.

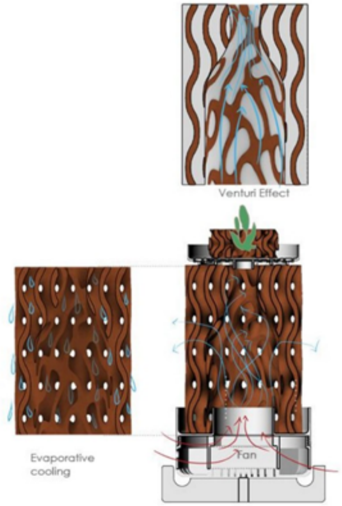


Figure 61. Assisted cooling with a desktop fan.

Figure 59. Biomimetic inspiration on termite mounds for airflow.

Figure 60. Closeup of infill.

Figure 57. Passive cooling tower concept for architectural use.

TerraMound

by Rameshwari Jonnalagedda

Location: London, UK
Year of completion: 2023
Category: Large-Scale Additive Manufacturing

Project properties

Material: **Clay**
Technology: **Delta printer**
Scale: **Product**
Application: **Cooling columns**

Printing location: **Off-site**
Post-processing of prints: **Bisque firing**
Support: **None**
TRL: **3**

Features

evaporative cooling

biomimicry

Key principles

- Complex geometry control (for maximizing surface area).
- Porosity.
- Variable infill density.

Description

TerraMound applies the age-old principle of evaporative cooling to 3D-printed ceramics whose shapes are optimized for airflow, and therefore optimized for cooling.

Discussion

Evaporative cooling takes advantage of the porosity of bisque-fired clay. As water slowly evaporates from within the porous clay object, it cools the air around it; improved airflow around the object maximizes this cooling effect. The shapes TerraMound uses are only achievable through 3D printing and they are the result of infill geometries such as gyroid, Swcharz P, diamond, and split P.

This is another example of passive cooling for buildings. Though it is possible and has been achieved with traditional building techniques in the past, 3D printing provides an opportunity to maximize the cooling capacity of each clay brick.

References

All images and details sourced from:
Jonnalagedda, R. (2023). TerraMound - Exploration with TPMS Geometries. Bartlett School of Architecture, University College London.

Figure 62. 3D-printed, bisque fired and glazed ceramic prototype.

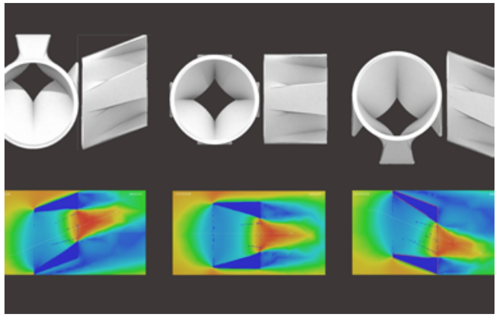


Figure 63. Effect of geometry on air passthrough.

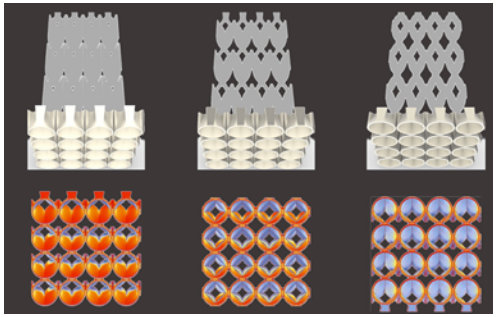


Figure 64. Effect of geometry on light passthrough.

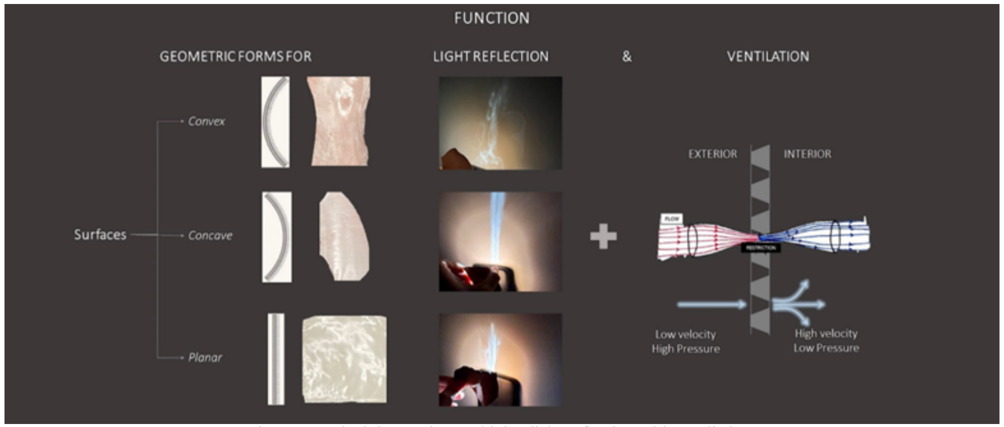


Figure 65. Principles used - combining light reflection with ventilation.

Ceram-Screens

by Monisha Sridhara

Location: London, UK
Year of completion: 2022
Category: Large-Scale Additive Manufacturing

Project properties

Material: **Clay**

Technology: **Delta printer**

Scale: **Architectural**

Application: **Facade screen**

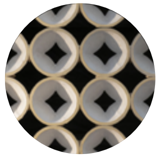
Printing location: **Off-site**

Post-processing of prints: **Bisque, glazing**

Support: **Mortar**

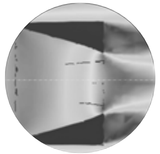
TRL: **4**

Features



visibility

shading



ventilation

Key principles

- Parametric geometry control.
- Porosity.

Description

Ceram-Screens creates geometries that allow light manipulation, influencing privacy, the effects of solar radiation, and ventilation simultaneously.

Discussion

This is an excellent example of an integrated solution that combines three different features into a single geometry. Facade screens are very commonly used in architecture but are typically made up of identical bricks that are no optimized in terms of radiation, ventilation, or the building's solar envelope.

Ceram-Screens also makes use of the reflective power of ceramic glaze. Its three features compliment and restrict each other, leading the designer to arrive at a form that achieves all three. For instance, a concave geometry is combined with a reflective glaze, while at the same time creating an opening in the middle of said geometry that influences visibility and ventilation.

References

All images and details sourced from:
Sridhara, M. (2022). Ceram-Screens. Bartlett School of Architecture, University College London.

New Delft Blue

by Studio RAP

Location: Delft, the Netherlands
Year of completion: 2019
Category: Large-Scale Additive Manufacturing

Project properties

Material: **Clay**

Technology: **6-axis robotic arm**

Scale: **Architectural**

Application: **Tiled archway**

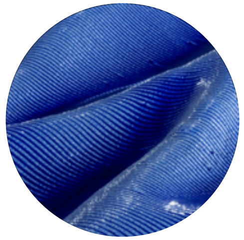
Printing location: **Off-site**

Post-processing of prints: **Bisque, glazing**

Support: **Cladding**

TRL: **9**

Features



new aesthetics

Key principles

- Computational and algorithmic design.

Description

New Delft Blue is a commercial project inspired by the centuries-old craft of Delft Blue porcelain. It attempts a reinterpretation of the aesthetic values of porcelain craftsmanship through digital fabrication tools.

Discussion

This project showcases the freedom of artistic expression offered by LSAM. As a relatively new craft, LSAM has been explored by many studios, artists, and designers in terms of its materiality and its aesthetic possibilities. This project is exemplary in its embodiment of the historical significance of the site and its reimagining of traditional values. A project like this poses the challenge of harmonizing the speed and efficiency of modern design and manufacturing tools (along with their resulting design language) with the heritage value of the traditional craft.

The reinterpretation of cultural heritage is highly subjective and tricky in its execution. However, the fact persists - as new technologies are popularized and their use becomes widespread, it becomes imperative for designers to serve as translators between the past and future, and to find ways to bridge these two respectfully.

References

All images and details sourced from:
Studio RAP. (2019). New Delft Blue. Retrieved from Studio RAP: https://studiorap.nl/New-Delft-Blue

Figure 69. Tiles assembled into an archway.

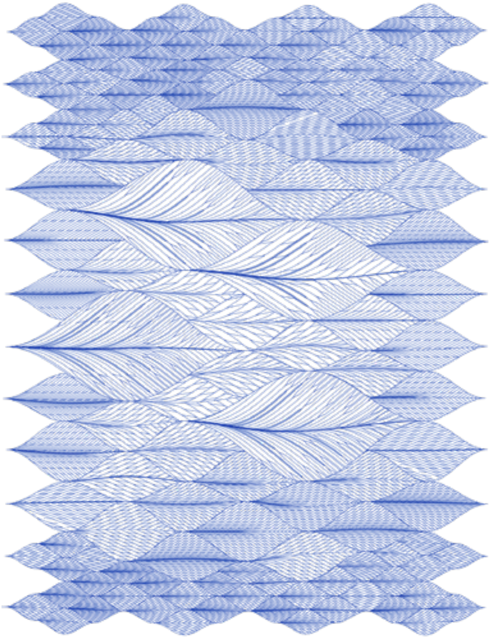


Figure 66. Algorithmically-designed, nature inspired pattern.

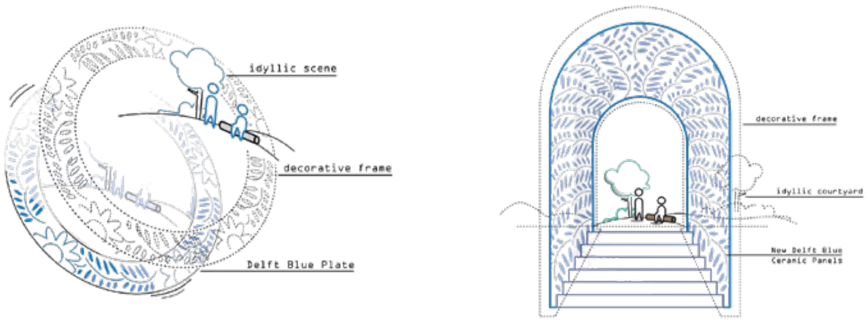


Figure 68. Design concept showing the site-specific inspiration for the design of the tiles.

Figure 67. Details of the tiles showcasing the design features that result from layer-on-layer manufacturing.

62

Figure 71. Timber elements integrated into the design of the house.

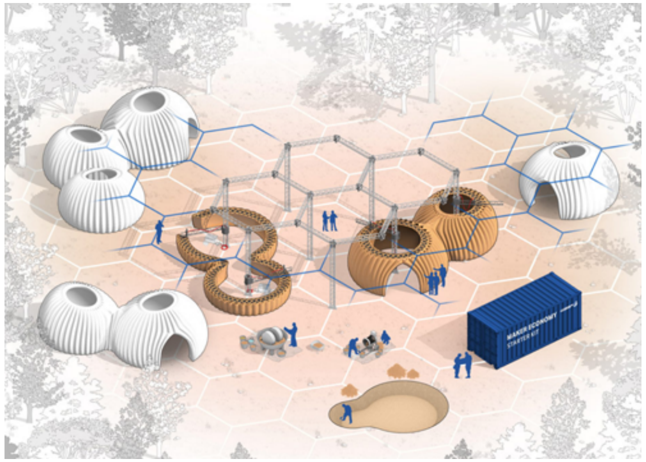


Figure 70. WASP's "Maker economy starter kit", an LSAM system that includes material sourcing, processing, and printing facilities all in one place.

Figure 73. Detail of an interior wall.

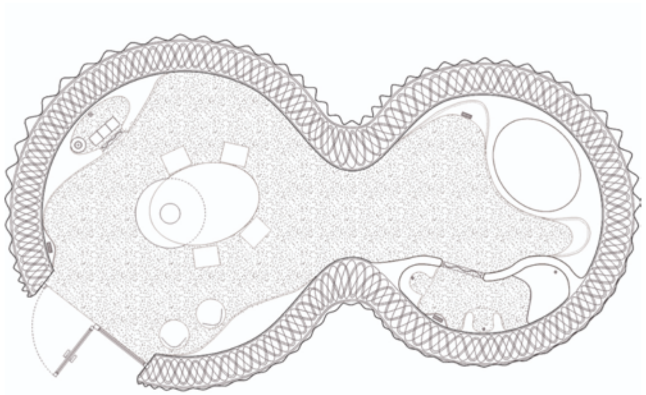


Figure 72. Top view section drawing of the house, showing the infill used for insulation in the walls.

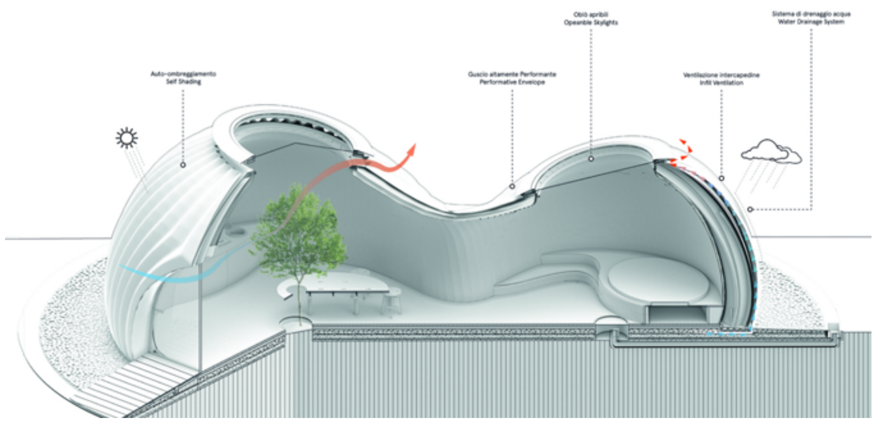


Figure 74. Section drawing showing all the integrated, climate-adaptive features of the house.

TECLA

by WASP and Mario Cucinella Architects

Location: Ravenna, Italy
Year of completion: 2021
Category: Large-Scale Additive Manufacturing

Project properties

Material: **Raw earth**

Technology: **Gantry system**

Scale: **Architectural**

Application: **House**

Printing location: **On-site**

Post-processing of prints: **None**

Support: **None**

TRL: **6**

Features

integrated support elements

km0 material

Key principles

- Printability of paste-like materials.
- Parametric geometry control

Description

TECLA is a low-carbon housing prototype printed on-site using raw earth sourced from a nearby riverbed. It combines the design and engineering advantages LSAM in construction with the sustainability benefits of local, "km 0" material sourcing.

Discussion

Extrusion-based printing has been seen achieved with a wide range of materials. This makes it possible to combine the possibilities offered by 3D printing with each specific material's properties. In fact, the material-driven design of 3D printing applications becomes essential to the development of smart sustainable solutions as the arsenal of printable materials expands.

Material features, however, are not limited to their aesthetic, mechanical, or chemical properties. In the case of TECLA, it is the sustainability of local material sourcing that acts as a conditioning factor for the project. Raw earth has been used as a construction material for centuries, but its potential in this case is shown in its carbon and energy efficiency, and its recyclability (all of which are highly compatible with 3D printing. It proposes a solution for fast and efficient temporary housing construction that is also circular.

References

All images and details sourced from:
WASP & Mario Cucinella Architects. (2021). TECLA. Retrieved from 3D WASP: https://www.3dwasp.com/en/3d-printed-house-tecla/

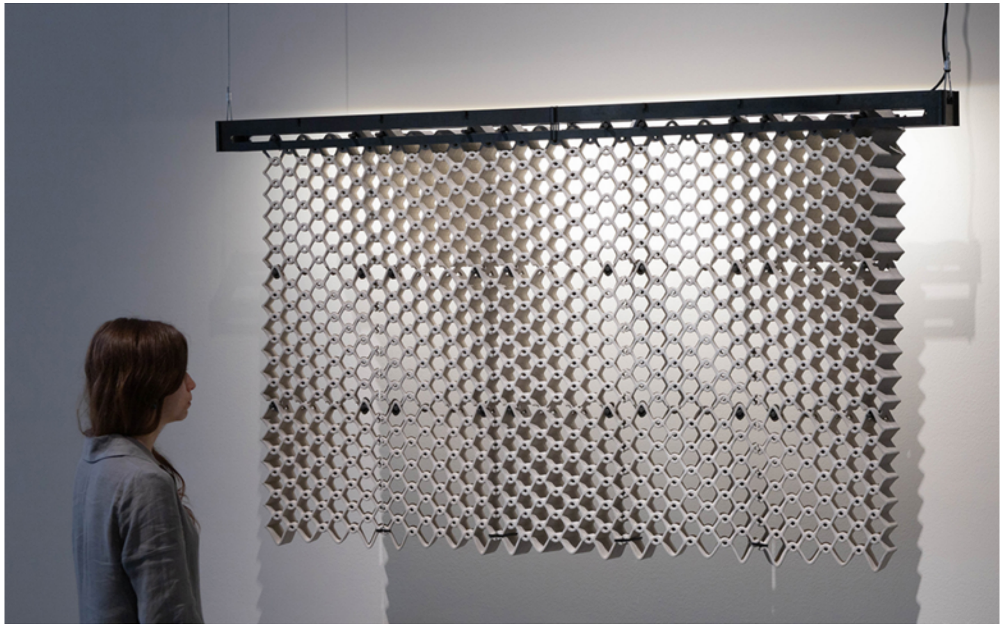


Figure 75. Screen in exhibition context.

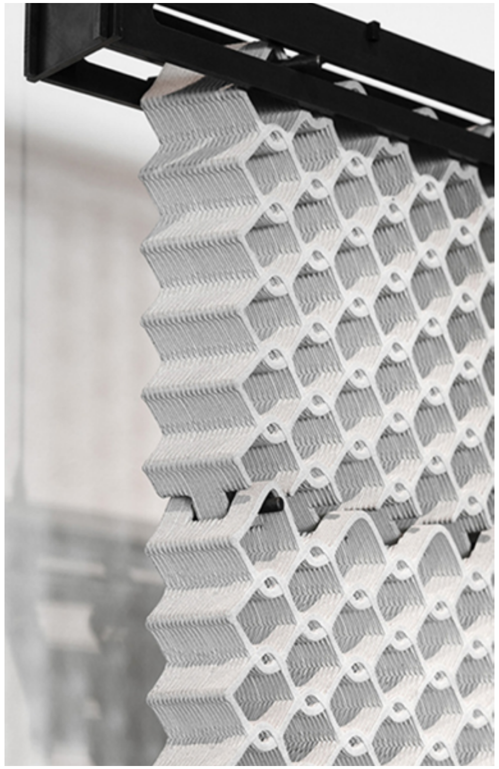


Figure 76. Interlocking 3D-printed components.

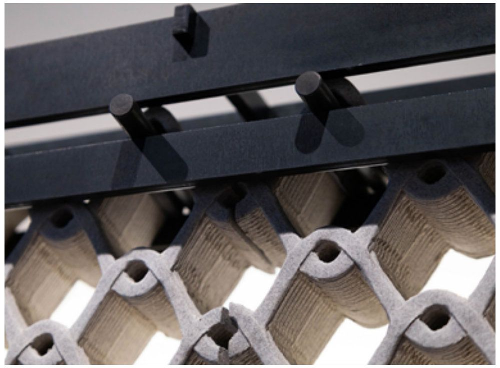


Figure 78. Mounting detail with integrated supports.

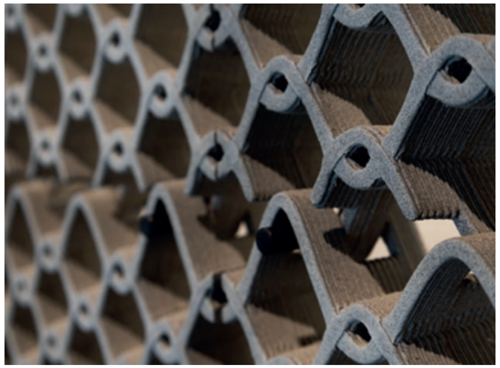


Figure 77. Print detail showing overlapping printing paths.

Static Shift

by Isabel Ochoa, James Clarke-Hicks, and David Correa

Location: Waterloo, Canada
Year of completion: 2023
Category: Large-Scale Additive Manufacturing

Project properties

Material: **Clay**

Technology: **SCARA printer**

Scale: **Product**

Application: **Hanging screen**

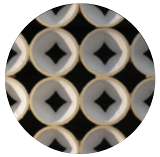
Printing location: **Off-site**

Post-processing of prints: **Bisque, glazing**

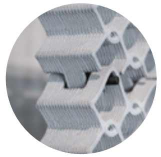
Support: **Curtain rod**

TRL: **5**

Features



visibility



interlocking components

integrated support elements

Key principles

- Parametric geometry control.
- Porosity.

Description

Static Shift is another project by OCH Works, a research and design studio led by Isabel Ochoa and James Clarke-Hicks. It is a parametrically-designed hanging screen with openings that

Discussion

Static Shift is unique in three distinct ways: firstly, the parametric geometry control enabled by algorithmic software enables precise control of the visibility angles of the user relative to the screen; secondly, it supports its entire hanging weight mechanically; and thirdly, it features components whose mounting is enabled both by the design of interlocking geometries, as well as the integration of non-3D-printed support elements. This makes the design highly modular and customizable, and eliminates the need for mortar, glue, or any type of adhesive. If applied to Adaptive Reuse, this feature should allow for non-invasive, removable, and modular interventions.

References

All images and details sourced from:
Ochoa, I., Clarcke-Hicks, J., & Correa, D. (2023). Static Shift. Retrieved from OCH Works: https://ochworks.com/static-shift

Figure 79. Panels installed at the Immersive Design Lab at ETH Zurich.

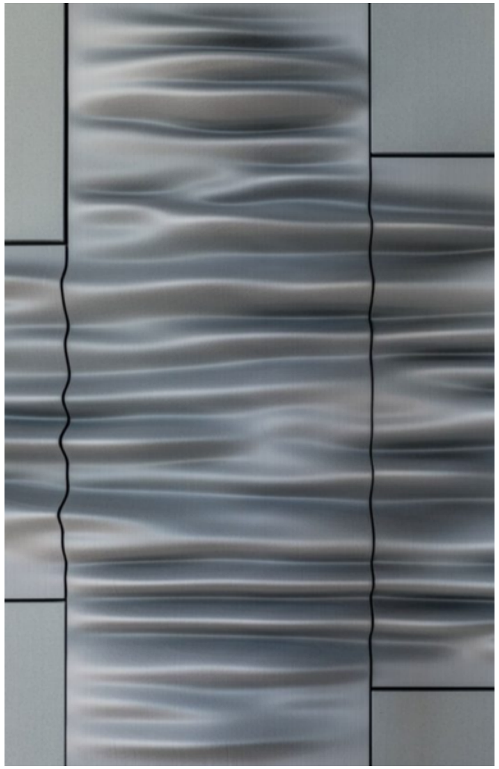


Figure 82. Panel assembly.

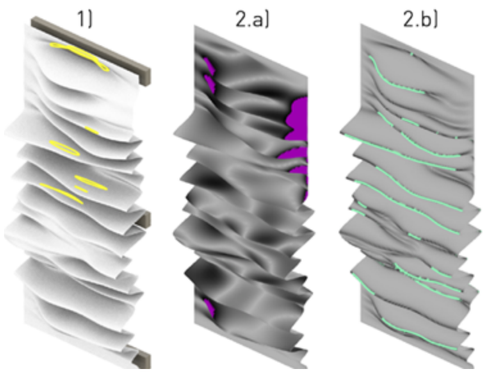


Figure 81. Fabrication constraints: 1) intersection with cladding, 2.a) Areas with large overhangs, 2.b) Areas with small curvature radii.

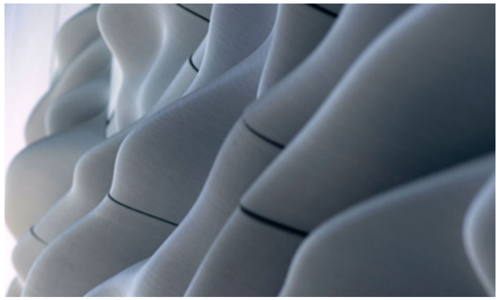


Figure 80. Close up of panels.

Soundwave

by Gramazio Kohler Research & ETH Zurich

Location: Zurich, Switzerland
Year of completion: 2021
Category: Large-Scale Additive Manufacturing

Project properties

Material: **Plastic (various)**

Technology: **6-axis robotic arm**

Scale: **Product**

Application: **Acoustic panels**

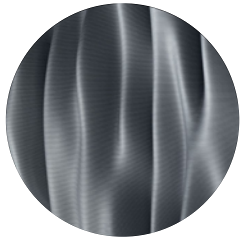
Printing location: **Off-site**

Post-processing of prints: **None**

Support: **Cladding**

TRL: **9**

Features



sound dampening

Key principles

- Parametric geometry control.
- Computational and algorithmic design

Description

Soundwave is a research project by Gramazio Kohler and ETH commercialized by Dutch 3D printing company Aectual. The research looks into the effects of panel geometries on sound diffusion, rather than the material they are made of.

Discussion

The outcome this research is a set of modular panels that result from an optimized algorithmic design tool developed by ETH researchers which enables the generation of variable geometric patterns for doubly-curved, undulated panel surfaces optimized for diffusion and fabricability. That is, it produces geometries that maximize sound diffusion within the constraints of 3D printing.

Additionally, although the geometry shown here is the one commercialized by Aectual partly because of its aesthetic qualities (which match the brand's style), the researchers tested over 130 geometries, many of which presented excellent acoustic qualities, which means that sound diffusion is not limited aesthetically to this particular shape.

References

All information sourced from:
Xydis, A. (2023). Data Driven Acoustic Design. Zurich: ETH Zurich.
All images sourced from: Gramazio Kohler Research & ETH Zurich. (2021). Acoustic Diffusor Panels, Immersive Design Lab. Retrieved from Gramazio Kohler Research: https://gramaziokohler.arch.ethz.ch/web/e/projekte/429.html


Figure 84. Screen in exhibition context.


Figure 83. Screen in exhibition context.


Figure 85. Detail of 3DCP structure wrapped around one of the columns.

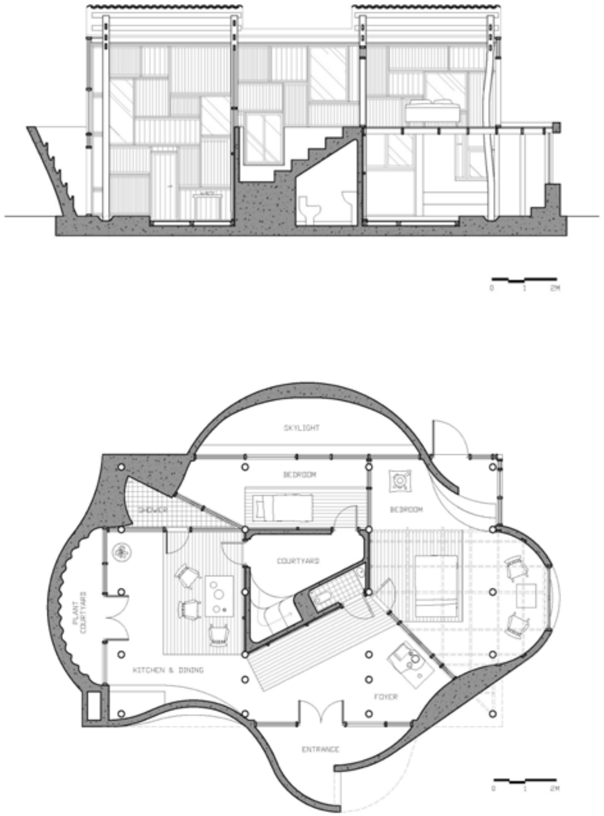


Figure 87. Section drawings showing the concrete foundation and the new amenities it incorporates into the design of the house.


Figure 86. Newly built kitchen and plant courtyard.

Traditional House of the Future

by Lidia Ratoi and John Lin

Location: Guiyang, China
Year of completion: 2023
Category: Large-Scale Additive Manufacturing for

Project properties

Material: **Concrete**

Technology: **6-axis robotic arm**

Scale: **Architecture**

Application: **Revamped house**

Printing location: **On-site**

Post-processing of prints: **None**

Support: **None**

TRL: **6**

Features


integrated support elements


integrated design elements

Key principles

- Parametric geometry control.
- Toolpath mapping onto 3D-scanned objects.

Description

Traditional House of the Future proposes a strategy for the revitalization of traditional Chinese vernacular houses. It features a 3D-concrete-printed foundation that adds modern amenities (such as bathrooms and plumbing) to the house.

Discussion

Traditional House of the Future is the only case study that uses LSAM in adaptive reuse. Instead of using the technology simply to repair a house and support its structural integrity (which it also does), it modernizes it and adapts it for use in the 21st century. The project looks at the newfound needs of the village's residents (the lack of modern amenities in their traditional houses) and designs an intervention that both repairs and revamps the house.

The house is scanned and a 3D-printed foundation is designed to wrap around the pre-existing structure, which is removed and reconditioned using traditional techniques. The house is then reassembled inside the printed foundation with the help of the villagers. The project therefore touches on key areas of social, cultural, and technological sustainability. It respects the original building fabric, it adapts to the needs of its users, and it includes them in decision-making throughout the project.

References

All images and details sourced from:
Ratoi, L., & Lin, J. (2023). Traditional House of the Future. Retrieved from Arch Daily: https://www.archdaily.com/1002291/traditional-house-of-the-future-lidia-ratoi-plus-john-lin?ad_medium=gallery

Conclusions on the LSAM case studies

In previous chapters we discussed that 3D-printed forms have a unique materiality that results from the layer depositioning process. The first thing that becomes clear after analyzing projects that use a variety of materials and post-processing techniques is that printing with mono-materials makes the material itself a primary contributor to the materiality of the design. In fact, though the features identified through this research are enabled by 3D printing principles, they are just as much enabled by the properties of the materials used, in many cases.

"Printing with mono-materials makes the material itself a primary contributor to the materiality of the design and the overall success of the project."

Grading Light uses porcelain's translucency in combination with varying layer widths to achieve light scattering, *TerraMound* uses bisque-fired ceramics' porosity combined with maximal surface geometries to facilitate evaporative cooling, and *TECLA* derives most of its value from the sourcing of local materials. Large-Scale applications of Additive Manufacturing often harness the power of materials through the creative interplay of material properties and 3D-printing-enabled geometries. Taking this into account, material choice becomes crucial in an LSAM intervention. This is also shown in the implications of post-processing materials like ceramics, whose shrinkage presents significant hurdles to overcome when producing dimensionally-accurate designs – we see this in the *Free-form Ceramic Vault System*.

Dimensional accuracy is especially important when piecing together a puzzle made of separate 3D-printed parts. One would expect most of these projects to be printed in one piece, since the machines used allow for the printing of very large objects. However, an advantage of AM is the cost efficiency of producing unique geometries at scale; when harnessed effectively, this enables great creative and logistic freedom, as the optimal dimensions for a piece can be adjusted depending on transport, access to the site, post-processing (such as firing ceramics), or modularity.

In some of these projects, the modularity enabled by 3D printing is used to make the pieces fit with other architectural elements, such as in *Static Shift* and *Soundwave*. This could open up a discussion into how 3D-printed architectural elements dialogue with the surrounding architecture – especially when used as part of a puzzle rather than as standalone pieces. One project proves very promising in terms of this puzzle-like integration of AM in architecture: *Robotic Restoration*. This is the most advanced, published project on printing missing parts of a larger whole on site. In artefact restoration, 3D printing has been used to repair missing or broken fragments; however, when printing large objects on location, the machine's limitations provide rigid constraints. As can be seen in the analysis of *Robotic Restoration*, accessing small crevices in wall gaps seems impossible, even with clever tool design.

"Depending on the site, designs can be adapted to not only fit the damage present, but also to satisfy the logistic intricacies of the intervention."

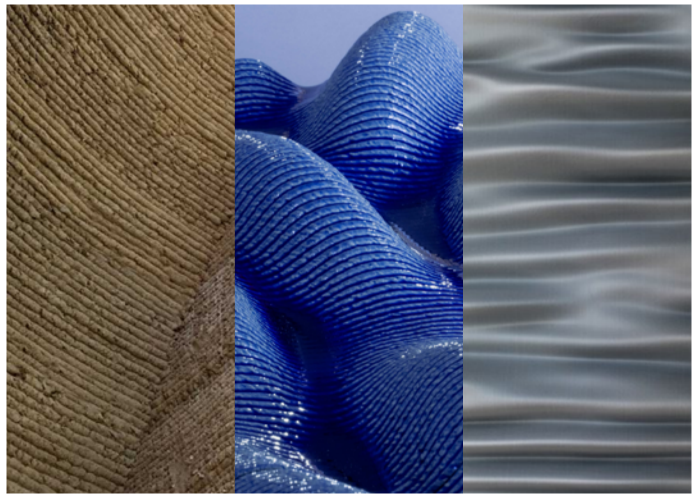


Figure 88. Materiality of raw earth, glazed stoneware clay, and plastic as seen in the LSAM case studies.

It is easily noticeable that all these projects, save for *New Delft Blue* and *Soundwave*, are research or exhibition projects. Most of them have a relatively low TRL, due to the immaturity of the technology. As we mentioned in the LSAM theory, these machines have hardly been commercialized; they are expensive, sometimes unreliable, and require clever engineering in order to be outfitted with 3D printing accessories. Each research center, studio, and company has their own proprietary technology and slicing software, which makes the sharing of knowledge slow and difficult. What is more, LSAM provides a high barrier of entry for design and architecture students, as it still presents a steep learning curve that cannot always be scaled in the timeline of a university project.

Still, the technology is mature enough that it can be explored for research purposes with far-reaching implications. It becomes clear after studying these cases that parametric geometry control is one of the great enablers of this technology. It seems natural that the production flexibility of LSAM is coupled with the design flexibility of parametric tools, and all of these projects do just that. LSAM can be seen as an outlet for parametric and computational design; it enables the integration of physical objects into the design of the printed part, gradient material properties, geographically-optimized shading and ventilation solutions, modularity, and custom-made acoustic paneling. Forgetting, for a moment, about the limitations of AM, one can measure its potential in the opportunities for parameterization of design and construction processes.

"One can measure the potential of AM in the opportunities for ***parameterization*** *of the design and construction process."*

In a sense, parametrization enables porosity as well; yet it is used so much in LSAM projects that it begs to be treated as a separate principle. Designing porosity into an object can be done through large openings in the geometry, but it can also be done on a much finer scale through toolpath variability. The precise control of each point in the G-code, coupled with the plasticity of materials like clay and plastic, allow for the creation of porous surfaces that in the context of this project, facilitate light scattering, ventilation, visibility, shading, and evaporative cooling.

Finally, *Traditional House of the Future* must be discussed separately from the other projects. It is the only case of LSAM being used in Adaptive Reuse currently published. Traditional House of the Future could be analyzed as an Adaptive Reuse project (this can be seen in Appendix X), however, it is more interesting to look at it from a 3D printing perspective. It provides a blueprint for interventions in vernacular architecture and starts an interesting discussion in its use of concrete combined with traditional materials. It exemplifies the potential of LSAM and parametric design when integrated into the current workflow of preservation, as well as their potential in the modernization of traditional architecture.

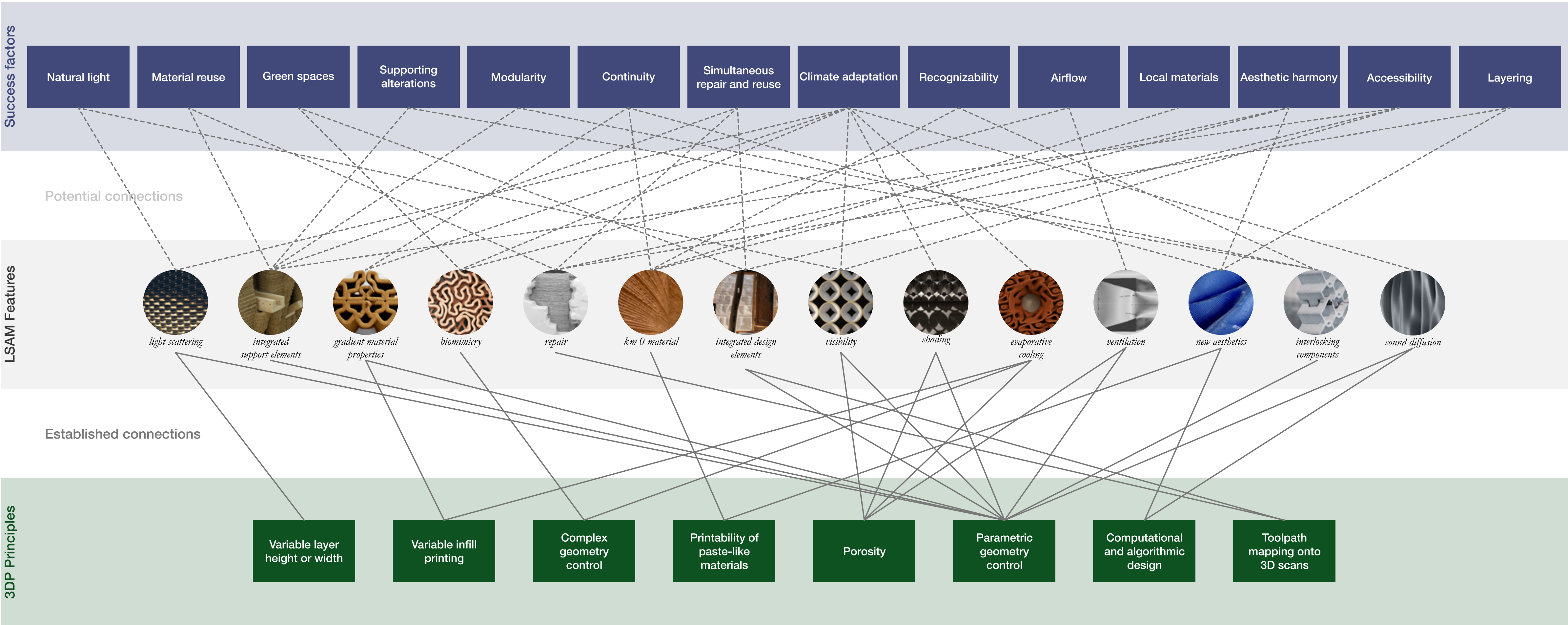
Opportunities for LSAM in Adaptive Reuse

Design-related success factors, features, and 3DP principles

In the AR case studies, we used a range of success factors were used visualize the impact of Adaptive Reuse works. These success factors were previously divided into general success factors and design-enabled success factors, interpreting the latter as influenceable by design choices.

Seeing as the features identified in the LSAM case studies are unique to 3D printing and pertain to the design of 3D-printed objects, we can draw some potential connections between the design-enabled AR success factors and LSAM features.

For instance, light scattering, enabled by varying layer widths and porosity can help bring natural light into a revamped building; the new aesthetics of 3D printing, enabled by computational and algorithmic design, can create recognizable designs that contribute to the historical layering of interventions and achieve aesthetic harmony between the original fragments and the 3D-printed parts; integrated support elements, enabled by parametric geometry control, can bring modularity and accessibility to the sites, as well as incorporate fragments of the original building fabric into the printed pieces.



These proposed connections speak to the potential for value creation in Adaptive Reuse through Large-Scale AM. The next phase of the project, a site-specific intervention, focuses on materializing some of these potential connections.

Figure 89. Design tool; mapping of design-enabled success factors, LSAM features, and 3D printing principles.

Part III
Applying the theory

Designing an intervention for a real-world case study

Site selection

Moving on to the last part of the project, we proceed to a site-specific application of the theory gathered in the previous sections. This includes finding a site, analyzing and identifying opportunities within it, and designing an intervention for it.

Site selection suggestions

Our design tool guided us in the final site selection and evaluation, as well as in brainstorming potential interventions. However, site-finding within the timeframe of this project was also subject to feasibility constraints. The complete guidelines followed in the site-finding phase are outlined here:

- **Presence of damage**. For a site to warrant an intervention, there must be some type of superficial damage to the building. This provides a canvas for the intervention and warrants its integration with the existing structure rather than its addition as an exhibition piece. The type of damage present will have to be assessed according to the technological constraints of the intervention. As we saw in the LSAM case studies, wall gaps provide significant geometric restrictions. Therefore, we must look for a balance in the complexity of the gaps in order to guarantee the success and survival of the intervention.
- **Proposed reuse**. It is useful (though not entirely necessary) for the building to have a proposed reuse. This could be a modernized version of its original use (as in Traditional House of the Future), or an entirely new one. Were the building not to have a proposed new use, one would have to be brainstormed through research and brainstorming with preservation specialists that are familiar with the site.
- **Cultural significance**. The cultural significance of the site is also an area that requires a balanced approach; going too far back in time will make the intervention controversial, but more modern sites might not provide enough room for improvement. The materials used and the aesthetic dialogue between the intervention and the original building fabric will largely depend on the cultural and historical significance of the site, as well as the traditional materials and building techniques used in it.
- **Accessibility**. The site must be easily accessible for analysis and measurement. Additionally, the presence of experts on site will provide much needed assistance in understanding the type of damage present, the site's history, and its evolution through time. If experts were not available on site, they should at least be reachable virtually in order to assist with the site analysis.
- **Presence of records**. In addition to experts, the presence of records (historical and architectural) that document the use of the site and its typological characteristics is highly valued, since it will also contribute to a thorough, in-depth analysis.
- **Architectural typology and materials**. Depending on the typology of the site, a 3D-printed intervention could be more or less suitable. Looking for sites where there is room for the integration of printed elements is a subjective, but important task. Though it is not a requirement, a useful suggestion is to look for sites with materials that can also be used in 3D printing. Having a common material as a starting point should provide a solid starting point upon which to build the rest of the intervention.
- **Opportunities**. Based on the conclusions of the last chapter, there should be potential for added value creation in the intervention. Upon outlining the requirements of a site, it will be useful to cross-check the design tool and use it as a creative aid in the brainstorming process.

Site choices

Sites were explored through contact with two non-profit organizations in Greece: *Boulouki*, a collective of architects, engineers, and preservationists that conduct itinerant workshops on traditional building techniques; and *Piliko*, a team of architects, engineers, and material scientists that focus on sustainable design practices and natural materials.

Boulouki has access to a plethora of culturally and historically significant sites all over Greece; more importantly, however, they have in-depth knowledge about the architectural typologies of the sites, as well as access to local residents, craftsmen, and experts in the above mentioned fields of architecture and preservation. Piliko are experts in clay and raw earth architecture, which is highly compatible with 3D printing, as was shown in the LSAM case studies (Ochoa, 2021; Dubor, et al., 2019; Lange, et al., 2020; Codarin, 2020; Carvalho, Figueiredo, & Cruz, 2023; Jonnalagedda, 2023; Sridhara, 2022; Studio RAP, 2019).

Figure 90. Site choice no. 1: Cave houses in Thirasia

Cave houses in Thirasia

- Chronology: 18th century
- Site: Village with underground houses
- Material: Volcanic mortar, stone
- Damage: Wall gaps, volumetric losses
- New use: Revamped houses
- Contact org.: Boulouki

Figure 91. Site choice no. 2: Rammed earth dovecotes in Tripoli

Dovecotes in Tripoli

- Chronology: 19th century
- Site: Dovecotes (pigeon houses)
- Material: Raw earth (clay)
- Damage: uncertain
- New use: uncertain
- Contact org.: Piliko

The dovecotes presented an interesting chance to combine 3D clay printing with traditional raw earth blocks; however, the absence of superficial damages to the buildings, the lack of interest for their revamping, and the fact that there was limited to no information on their historical significance and architectural typology, created such a degree of uncertainty as to the feasibility of the intervention that they were ruled out after a first visit to Greece and an in-person meeting with Piliko.

The cave houses of Santorini, on the other hand, have been studied in depth by many authors because of their unique typology, and the site in Thirasia has been the subject of a recent intervention by Boulouki. Therefore, not only is there an active interest in rebuilding the village, but also abundant records on the architecture, history, cultural significance, and materiality of the houses.

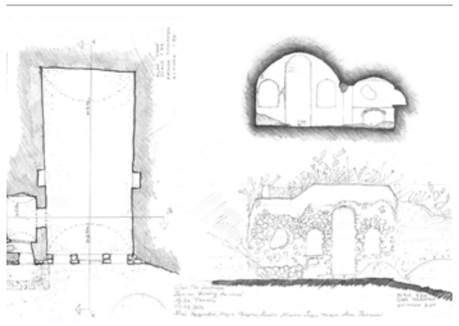
Cave houses in Thirasia

Presence of damage

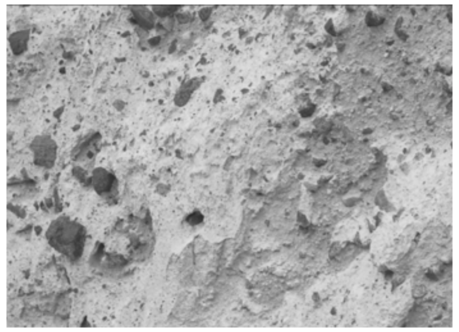
Proposed reuse

Cultural significance

Accessibility



Presence of records



Architectural typology and materials

Dovecotes in Tripoli

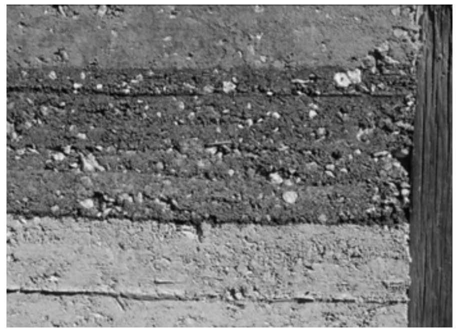
Presence of damage

Proposed reuse

Cultural significance

Accessibility

Presence of records



Architectural typology and materials

Figure 92. Site choice comparison based on the site-selection guidelines

Final selection

The site in Thirasia is the unique case of an abandoned village from the 18th century comprised exclusively of traditional cave houses identical to the ones of neighboring island, Santorini. The stark contrast between the mass touristification of Santorini and the gradual abandonment of Thirasia provides an excellent opportunity for a new, respectful approach to preservation.

Cave houses in Santorini and Thirasia are described by Efthymios Warlamis as archetypal constructions, emerging from the most primitive form of shelter and slowly growing outside of it and expanding into modernity (Warlamis, 1995). This unique typology has made them the subject of a number of architectural studies throughout the 20th century (Filippidis, 1983). However, mass tourism in Santorini has rendered the archetypal cave house a caricature. Since the 1990s, Santorini has undergone significant development, with annual tourist numbers reaching 3.4 million in 2024 in an island with a population of 25,000 (Smith, 2024). The domed white houses of the main settlements of the island have become the subjects of postcards and souvenirs, but the growing demand for lodging during the tourist season has made developers build with increasingly cheap materials and, in many cases, illegally, refusing to adhere to the strict building restrictions from the local archaeological authorities.

Houses in the archipelago were traditionally built with local materials, making use of the vast amounts of volcanic material left behind by the Minoan eruption of 1600BCE (Palivou & Tzaxili, 2015). One of the most commonly used construction materials is a type of volcanic mortar which research conducted by Boulouki suggests could be 3D printed, as it behaves similarly to cement-based mortar (Boulouki, 2022).

All this makes the case of Agrilia (the abandoned village in the island of Thirasia) one of not only crucial historical and cultural significance, but also – according to the site selection suggestions – compatible with 3D printing as a preservation technology, extremely well documented, well preserved enough to warrant a focalized intervention but with clear cases of damage, and with an urgent need for repair.

Site analysis

Methodology

The analysis of the site was done in two visits, leaving space for meetings with experts from Boulouki in between to help make sense of the data gathered in the first visit and prepare for a more in-depth analysis in the second one.

Visit 1

The first visit served as a preliminary exploration to identify opportunities for the project. Despite the vast amount of documentation available on the site, there was still a possibility of it not being suitable for this research. During this reconnaissance trip, the entire village was explored, the more interesting cases of damage to the houses photographed, and the locals were interviewed informally regarding their current needs and the problems the island is facing. All this served to form a general idea of the needs of the island and its residents, and laid the groundwork for brainstorming on potential solutions. Additionally, material samples were gathered from the site to experiment with in a laboratory setting and see their compatibility with 3D printing.

Figure 93. Initial surveying of the village.

Visit 2

After consultation with Boulouki, the site was visited a second time with the objective of gathering data that would allow for a rigorous analysis of the site, as well as tools to aid in the design of the intervention. During this visit, the more interesting houses in the village were surveyed and photographed, locals were formally interviewed, and one particular house was chosen as a case study, 3D scanned, and fully documented through drawings and sketches.

Figure 94. In-depth analysis of the village.

Analytical approaches

In order to effectively and holistically understand the needs of the site and design an intervention that is not only practical, but achieves continuity between the past and present, the village was analyzed from two different standpoints:

Cultural approach

Understanding the cultural and historical significance of the site involves tracing its development over time and analyzing the evolution of its architectural style, understanding its cultural influences and references, and how they are reflected in the built environment. A historical analysis of the village serves to place it in its broader regional context, assessing how local traditions and practices have shaped its identity. This is especially important in the case of Thirasia due to its proximity to Santorini, which has seen its cultural identity diluted by tourism.

Figure 95. The tourist port of Korfos, in Thirasia's NE shore.

Typological approach

From a typological perspective, the village was analyzed deductively. First, understanding its settlement patterns and spatial organization – the use of public space and the clustering of houses along the landscape. The village typology is inevitably connected to its historical, cultural, and environmental influences, and was therefore important to understand before delving deeper into its building typology. Cave houses in Santorini and Thirasia are typologically unique – their forms, layout, and architectural features are therefore studied in depth, as it is in these architectural features that damages are present and where the intervention will take place. Finally, the relationship between local resources, craftsmanship, and the cultural identity of the village is reflected in the houses' materiality. Said materiality constitutes the outermost layer of the site's complex significance, and for the intervention to achieve continuity between its past and present, the 3D-printed materiality must complement the vernacular.

Figure 96. Section drawings of a Theran house (Warlamis, 1995).

Analytical tools

More practically, in order to carry out this analysis, a variety of tools were used, some of which were already mentioned above:

Observation

Careful passive observation of the site was achieved through a prolonged stay in it. By experiencing its rhythms and effectively living in it for a short period, the taxonomy of the village and its relationship to is environment was better understood. Additionally, participant observation in personal interactions with the locals helped empathize with them and their needs, informing a holistic understanding of life on the island.

Figure 97. Participant observation in Agrilia.

Bibliography

Bibliography on the history of the island, as well as its architectural particularities was consulted for a more rigorous, scientific understanding of the village's taxonomy and its architectural history. It is important to note that the bibliography was not only consulted before, in between, or after the visits, but mainly during – the surveying and observation carried out on the site was strongly complemented by literature, since the architectural typology of the village and the houses is so unique that one cannot fully grasp it without the help of the architects that have studied before.

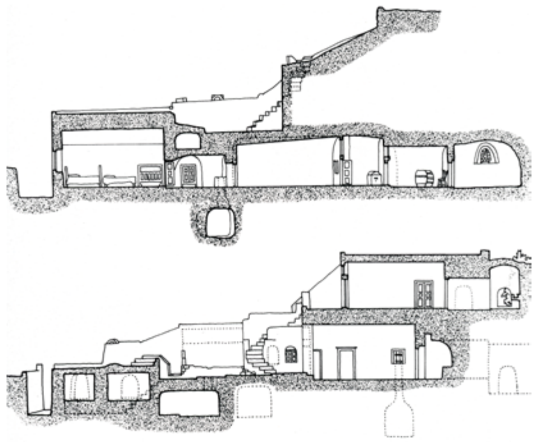


Figure 98. Section drawing of a house in Santorini (Warlamis, 1995)

Interviews

Both formally and informally, interviews with the locals provided answers to specific questions that arose during the visit. Thirasia is home to less than 300 permanent residents, and the best source of information that fills the gaps existent in literature often comes from the residents themselves, especially regarding their use of the built environment, their rites and customs.

Figure 101. Screenshot from interview with Agrilia's only remaining resident.

Surveying

Surveying and measuring was used to create accurate architectural drawings and artistic impressions of the houses that helped to analyze their use of space. Furthermore, the intervention's physicality warrants a precise reconstruction of the site to use in the design and prototyping process, as this happens far from the site. Therefore, images, drawings, and sketches were created as records mainly for their *a posteriori* consultation and analysis.

Figure 99. Measuring and surveying house no.37 in Agrilia.

3D Scans

Finally, photogrammetric 3D scans were produced as the ultimate reconstruction tool. Concurrently, scans of the gaps in the building envelope served as a direct tool in the design of the intervention.

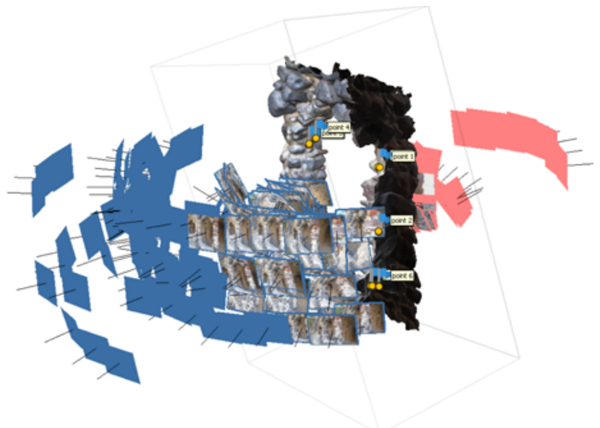


Figure 100. Screenshot from 3D scanning software Metashape.

History and cultural significance of Agrilia

Taking a cultural approach to the analysis first, this section outlines the main geographical, historical, and economic factors that have shaped life on the island and contributed to its architectural heritage. Understanding these influences was improtant not just to place the project in a broader cultural context, but to serve as input for the later design of the intervention, which draws inspiration from this analysis.

Geography and morphology

Abandoned soon after World War II in the rural flight that pushed people away from the countryside and towards the industrial hubs of Piraeus and Lavrion, Agrilia used to be one of the four main towns in the island of Thirasia (Palivou & Tzaxili, 2015). It is located in the central section of the island, southwest from the largest settlement of the island, Manolas.

Figure 102. Santorini island complex showing the main island of Thira and Thirasia (in red). The islands circle around the volcanic caldera in the center. Image sourced from the Greek Geographical Army Service.

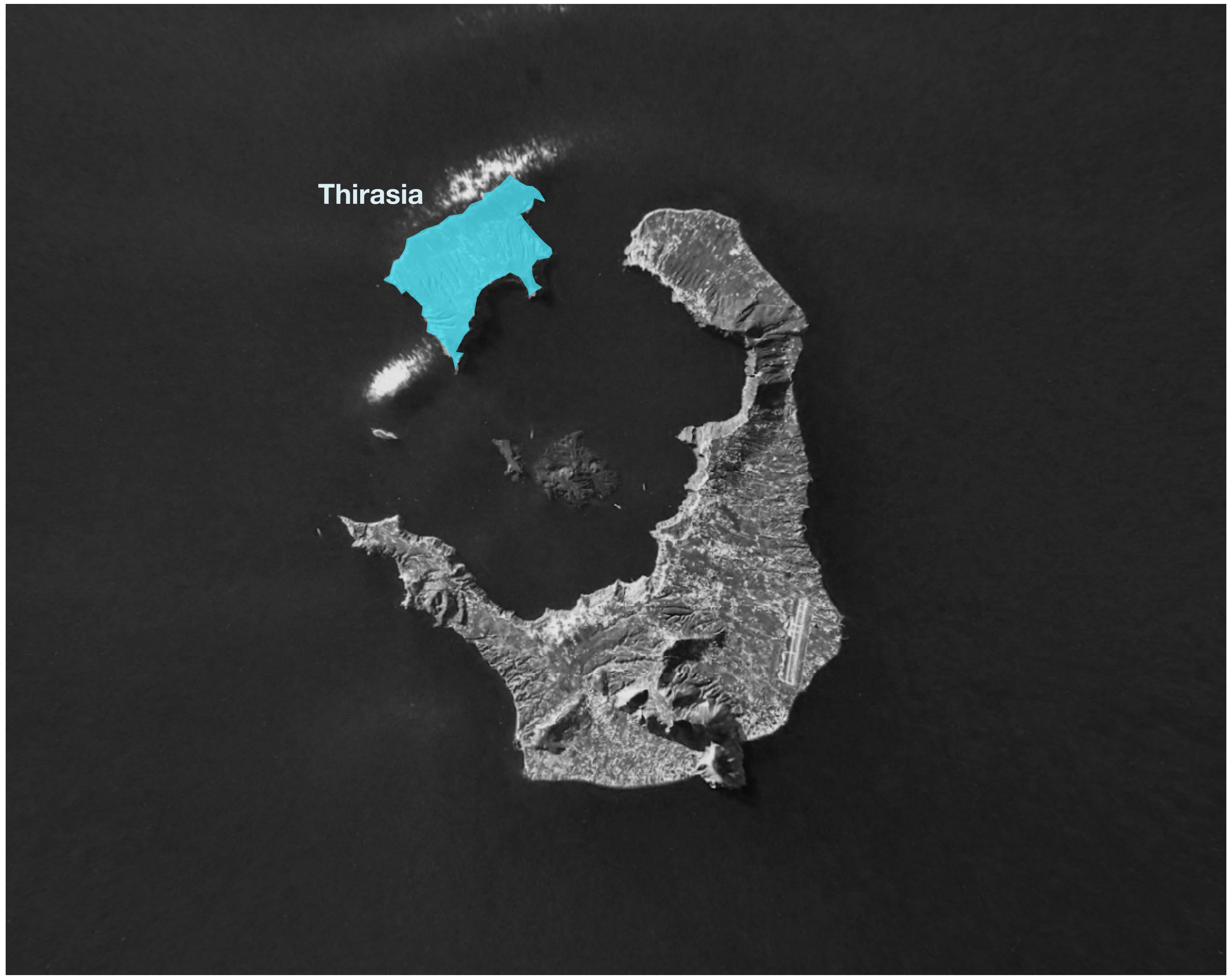


Figure 103. Location of the two largest settlements in the island of Thirasia and Agrilia's location with respect to them . Image sourced from the Greek Geographical Army Service.

Thirasia is part of the island complex of Santorini, which includes the main island of Thira – a tourist hub complete with three ports and an international airport, the largest in non-continental Greece. Thirasia and Thira were once part of the same island, that is until the Minoan explosion of ca. 1613BCE. After this explosion, the morphology of the island changed drastically, isolating Thirasia from the rest of the complex and covering the islands with thick layers of pumice and volcanic stone. The release of 60 cubic km of magma upwards and outwards from the caldera at the center of the complex engulfed Thirasia from the Southeast and created a downwards-sloping landscape that slowly faded into the sea on the Western side of the island (Vougioukalakis, 2015). This means the entire island is built on a slope, and this type of landscape allowed for the construction of a castle at the top of the hill – in what is now the main town of Manolas – and several smaller settlements in the ravines created by rainfall on the slopes. This is the case of Agrilia.

The geology of the island has not only influenced its morphology and distribution of settlements, it has also played a crucial role in its architecture and building practices and, consequently, in its economy. Agrilia was built and inhabited almost exclusively by workers of the Theran earth (or Theran tephra) mines, which extended along the northern and southern coasts of the island. In the early 20th century, the island was subject to major mining efforts that exported material to build the Suez Canal, in Egypt and the port of Trieste, in Italy (Papastefanaki, 2018). According to interviews conducted by Boulouki, locals remember Agrilia housing up to 1000 workers at its demographic peak, in the 1950s (Boulouki, 2022). However, the village's economy was also made up of other economic activities similar to those taking place in the rest of the island and its larger neighbor, Thira.

"Housing up to 1000 miners, Agrilia was once a workers' settlement, abandoned during the rural exodus of the mid-20th century."

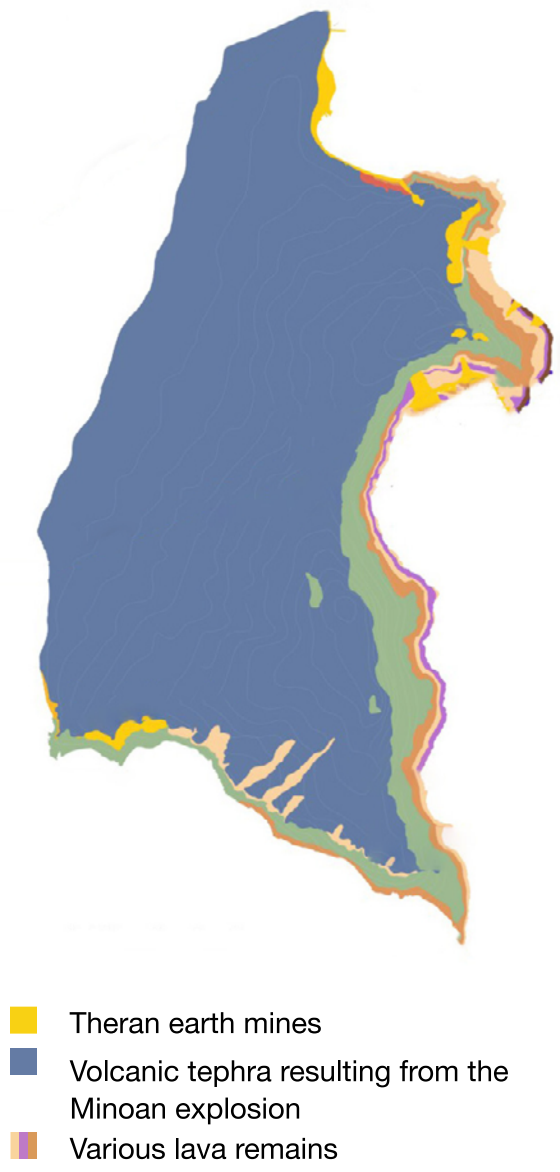


Figure 104. Lava remains and Theran earth that make up the geology of the island (left). Map of the geological composition of Thirasia (right). Images and map sourced from Boulouki (2022).

Figure 105. Section drawing of Thirasia, showing the slope that characterizes the island's landscape.

Economy

Since the mid-20th century, the island's population has decreased drastically, from close to 2000 in 1933 (Zorgos, 1933), to a meager 150-250 residents in the present day (Palivou & Tzaxili, 2015). Though it is separated from the main island of Thira by a marine passage of hardly two kilometers, Thirasia seems to have followed a reverse course of development, leading to its gradual abandonment, In fact, the population of the island nearly doubles in the summer, when so-called "seasonal residents" come to visit from their homes in Piraeus and Lavrion. These are the descendants of the workers that emigrated to the large Athenian ports after the mines shut down in 1970 (Douskos, 2015).

Therefore, the population of Thirasia is made up of seasonal residents, as well as a few hundred permanent residents, who make a living mostly from the tourism that spills over from the main island. The unlucky few that do not own hotels or restaurants, are forced to either commute to the main island or live off of the island's resources, which are scarce and have been severely impacted by climate change. Despite the dry climate of the island, Santorini has made a name for itself as a producer of Assyrtiko, its own regional wine. In fact, the winemaking tradition of the island dates back to its earliest settlers, and as will be shown in the village typology later on, every house on the island used to be equipped with its own vineyard and wine cellar. Nowadays, however, wine production has seen a steady decline due to droughts and a lack of interest in the arduous craft of grape collection, with most of the locals being slowly drawn to the hospitality sector.

The economic hub of the island lies in Korfos, its second port with no road access – only a steep stone path that leads up to the main village. Korfos is packed with restaurants that fill up with daily visitors; hundreds of boats sail every day from the main port of Santorini and take tourists around the caldera, stopping in Korfos for lunch or dinner, and providing Thirasia with its main source of revenue. However, isolated as this port is, tourists rarely venture up the hill and over to the rest of the island, where residents have made little effort to attract them anyway. This has made Thirasia, save for this small tourist port, a severely underdeveloped economy. A few boutiques and souvenir shops that are only open in the summer months, two small supermarkets, a bakery, and a hardware store are all available commerce on the island. Until recently, it had no pharmacy or ATM machine, and it still has no police, and no firefighting unit. Finally, the local school has a total of 22 pupils aged 5 to 18, most of which start working at their parents' businesses from a young age and more often than not, do not get to finish high school (Douskos, 2015).

Figure 106. Overbuilding in Thira. Unregulated and uncontrolled development has overcrowded the island's towns. In the background we see the underdeveloped landscape of Thirasia. Image sourced from KAYAK (2025).

Upon visiting Thirasia and interacting with the locals, it becomes apparent that its socioeconomic problems and the reasons that have led to its gradual abandonment and impoverishment are not the result of neglect, but of gentrification and mass tourism. Despite the invaluable archaeological, architectural, and cultural heritage of the island, Santorini attracts visitors that are merely interested in its superficial beauty – its beaches and cliffs, its famous white and blue domed houses, and its food. The local government has responded accordingly by boosting these attractors and neglecting any other forms of economic activity. Santorini acquired its airport in 1972 and its once small towns have expanded into each other, leaving very few undeveloped areas, despite the high density of archaeological sites all over the archipelago. The island's architecture has become a caricature of itself; the limewash that dresses the houses and makes for sparkly, white postcards hides the materials underneath. Developers have long ago relinquished traditional forms of building due to their high cost and need for skilled labor, and have resorted to building cheap houses made of cinderblocks and drywall – materials completely unsuitable for the humid climate of the island that have to be replaced yearly, creating space for developers to not only build, but rebuild year after year.

> *"Thirasia is currently where Santorini was 35 years ago; it now finds itself at a crossroads where it could choose to apply a sustainable tourism model."*

Modes of habitation

Santorini is an island of contrast. Its steep cliffs and deep ravines historically divided its inhabitants between the "visible and the invisible". Atop the island's tall cliffs are its largest settlements. Traditionally, these all-too-visible but geographically advantageous settlements were highly fortified and inhabited by the wealthiest members of society. Regular townsfolk lived more primitively, in caves carved out from the walls of the ravines (Palivou & Tzaxili, 2015).

The earliest mention of underground cave houses is made by François Richard in 1657, though cave dwellings are a famously prehistoric form of lodging and likely existed on the island long before that (Delendas, 1949). Due to Theran earth being made up mostly of volcanic pozzolan, which is very soft and easy to dig, it only made sense that the island's inhabitants developed a stereotomic approach to architecture, carving their houses into the face of cliffs. The traditional Theran house which is now revered as a symbol of Greek folk architecture is therefore the result of necessity and resource availability. This mode of habitation was favored due to the microclimate of the ravines (protection from the wind, water supply, ease of construction). It also provided protection due to the invisibility of the houses. Though Santorini is famous for its bright white domes, traditional houses in the island complex only began to be painted with limewash later on and, in the case of Agrilia, very few houses were painted at all, blending seamlessly into the landscape.

Figure 107. The "visible and invisible" forms of dwelling in Santorini, showcasing the contrast inherent in the island's morphology

Conclusions and design inputs

A variety of cultural and socioeconomic factors have influenced Santorini's development through the years and, in the past 35 years, have led it down a treacherous path. The rural exodus that led to the abandonement of Agrilia, among other settlements in the main island of Thira, turned the island's economy from one dependent on the exploitation of its natural resources, one dependent on tourism and foreign investments.

This shift is not unique to the archipelago; in fact, it is observable all over Greece. Santorini has grown so much because of tourism, that turning back to its old model of wine production and mining would prove economically unsound. Tourism cannot be driven away from the Greek islands, but it can change its approach. Thirasia provides a unique opportunity to set an example of respectful and sustainable heritage preservation; the houses in Agrilia will never be occupied by their former residents, but they can attract a form of tourism that is not interested in the caricaturistic representations of heritage of Thira. Additionally, an innovative approach to heritage preservation could also strengthen local building practices by shifting the public's attention from the island's overexploited natural beauty and overpriced lodging to its unique architectural heritage.

"An innovative approach to heritage preservation could highlight the island's architectural heritage, instead of its luxurious hotels and black sand beaches."

An intervention in Thirasia should focus on blending innovation into preservation in a way that highlights the uniqueness of Theran architecture. This architecture and its building practices are the result of necessity and resource availability, and these are values that should be translated into the intervention's approach. In its simplest form, this could mean using local materials and borrowing as much as possible from the locals' approach to building. Later on, when discussing traditional materials and building techniques, we will extract certain design inputs to effectively achieve this translation.

Finally, we saw how cave dwelling evolved from the original settlers' need to hide in plain sight. While a survival need like this one has no footing in contemporary society, the architecture of the island and its resulting heritage is directly influenced by this form of architectural camouflage.

Figure 108. Facade of a house in Agrilia blending in with the surrounding landscape thanks to its use of on-site materials.

The houses blend in seamlessly with the landscape, which suggests that an intervention carried out on the facade of any given house would also have to blend in. However, in the *Preservation theory and practice* chapter, we remarked how interventions are meant to be distinguishable from the original building fabric; therefore, a balance would have to be achieved between - to put it simply - blending in and standing out. This gives us our first design input:

Blending in
while standing out

Architectural typology of the village

Moving on from the island's cultural legacy, we can delve into an architectural analysis of the village. The case study at hand studies Agrilia as an architectural ensemble, and the intervention that was designed for it aims for the revival of the village as a whole. For this reason, the analysis must begin with the village typology before analyzing the houses as individual units.

A village created by rainfall

Thirasia's steep cliffs and gently sloping landscape force rainfall into channels that slowly dig into the soft Theran tephra and form a number of ravines that extend from East to West across the island's surface (Filippidis, 1983). Though ravines are sheltered from the elements, they provide an unusual setting for a village to develop. Houses extend lengthwise along the gorge and are not clustered around a central square or building, as they do in the "visible" settlements of the island.

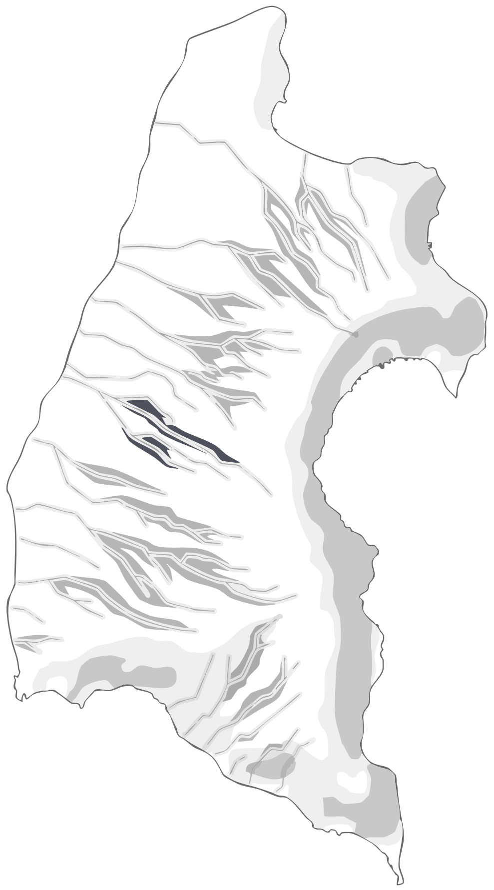
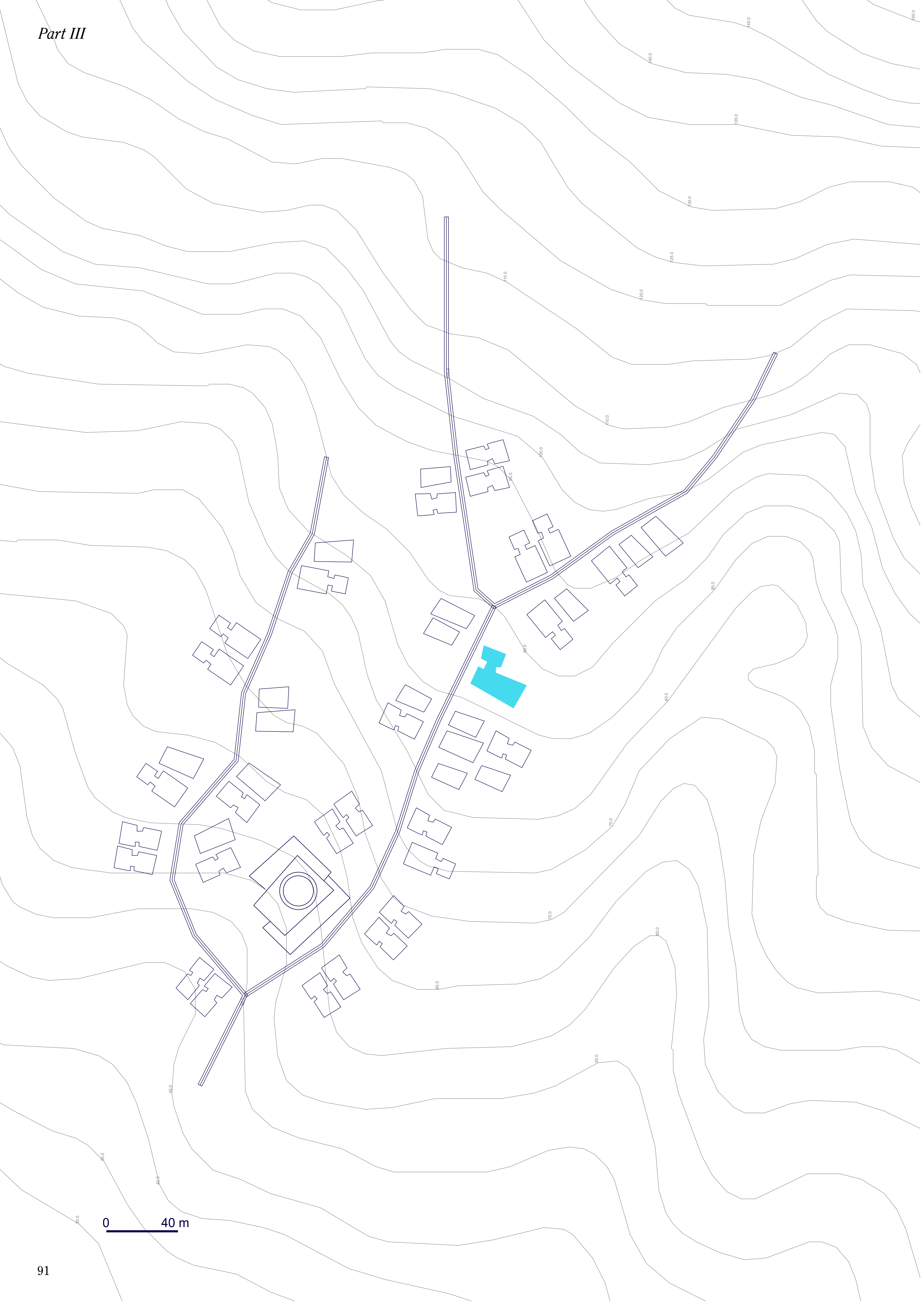


Figure 109. Location of the village of Agrilia within the island's network of gullies and aquifers.

Figure 110. Renovation of stone pathway and cistern carried out by Boulouki in 2021-22. Images sourced from Boulouki (2022)

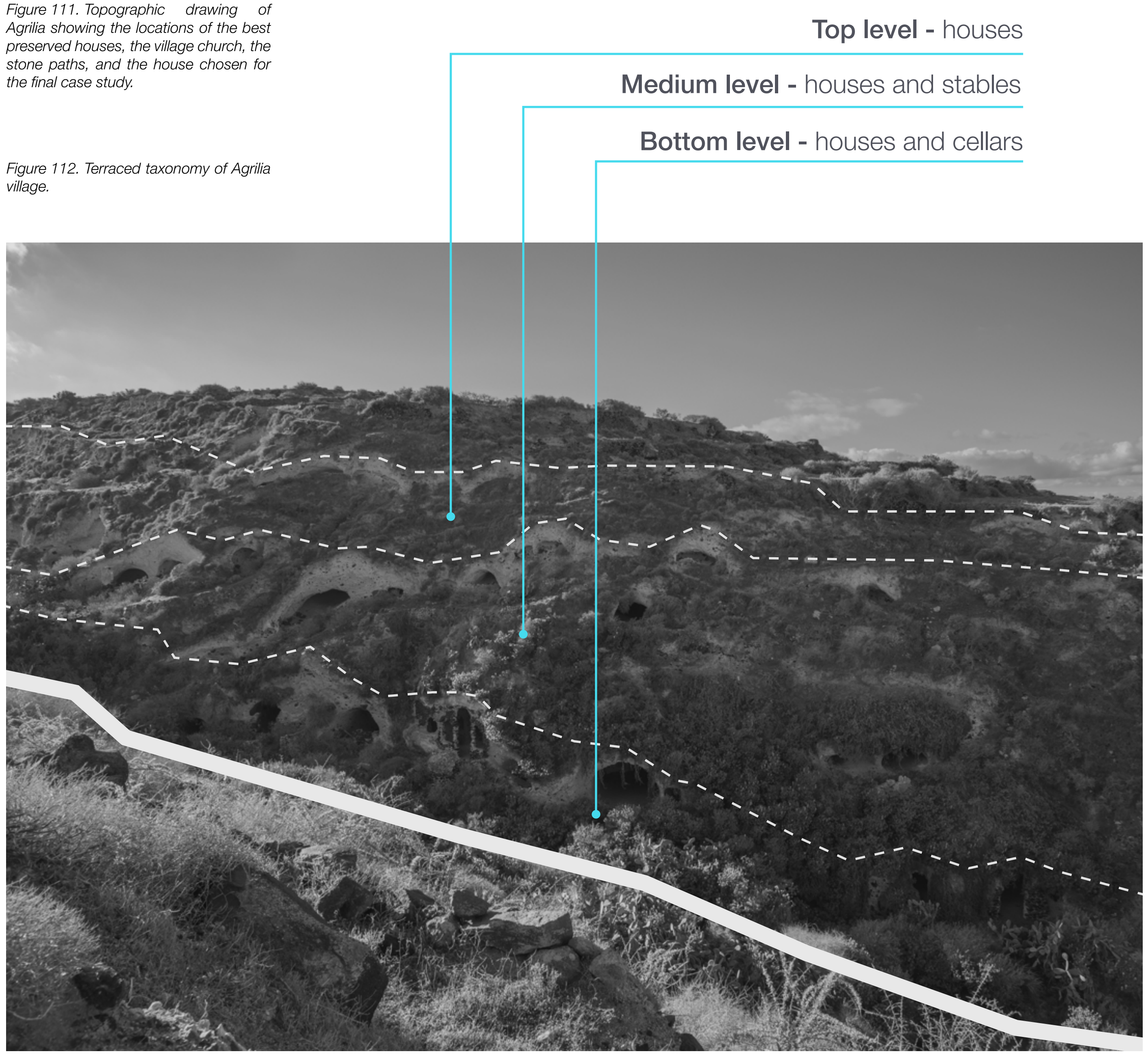
Houses therefore line the hillside on both sides of the ravine, distributed almost symmetrically across the central axis that runs along the center of the gorge. Along this axis, a stone path is meticulously planned and constructed using large volcanic rocks that facilitate the flow of water down the path in rainy seasons, effectively channeling the water into a number of underground cisterns on various points of the village. Incidentally, the southernmost path and two cisterns along it were the object of Boulouki's works of restoration in the island across 2021 and 2022 (Boulouki, 2022).



The height of the hills allows for multiple levels of building. Across the entire village, houses are arranged according to three distinct levels, each of which features a degree of decay relative to its altitude. That is, the top levels have been damaged by the elements and houses on this height are almost completely destroyed. Atop the hills are farming grounds, primarily used for farming grapes destined for wine production. Beneath the vineyards, a level of houses currently in very poor condition; in the middle level, houses and stables often connected to the level directly beneath them; and at the very bottom, the best preserved houses, each complete with their very own wine cellar.

Figure 111. Topographic drawing of Agrilia showing the locations of the best preserved houses, the village church, the stone paths, and the house chosen for the final case study.

Figure 112. Terraced taxonomy of Agrilia village.



The village as an indivisible whole

The linear distribution of housing units along the length of the ravines makes for a peculiar spatial arrangement that is unlike that of towns built on even ground. More specifically, the use of public space in the village changes as a result of the absence of a town square or any such central gathering space.

Amos Rapoport states that anonymous vernacular architecture cannot consider the house as an autonomous building unit, but rather must see it as part of a larger, indivisible whole (Rapoport & Filippides, 2010). This is particularly true in the case of Agrilia. The lack of public gathering spaces in the village means that social activities take place in the transitional spaces between houses – in this case, the stone paths. However, upon visiting Agrilia, one notices that housing units in the lower topographical level feature large courtyards – as large as the interiors of the houses themselves. Additionally, these courtyards are not delimitated by fences and therefore do not have access doors, but rather form part of the shared public space of the village. This points to social activities also taking place in said courtyards, with the cave houses themselves serving as the only truly private spaces in the village. Thus, life in Agrilia develops around the courtyards and stone paths, which collectively bind the village together and contribute to its indivisibility.

"Vernacular architecture cannot consider the house as an autonomous building unit, but rather must see the house as part of a larger, indivisible whole."

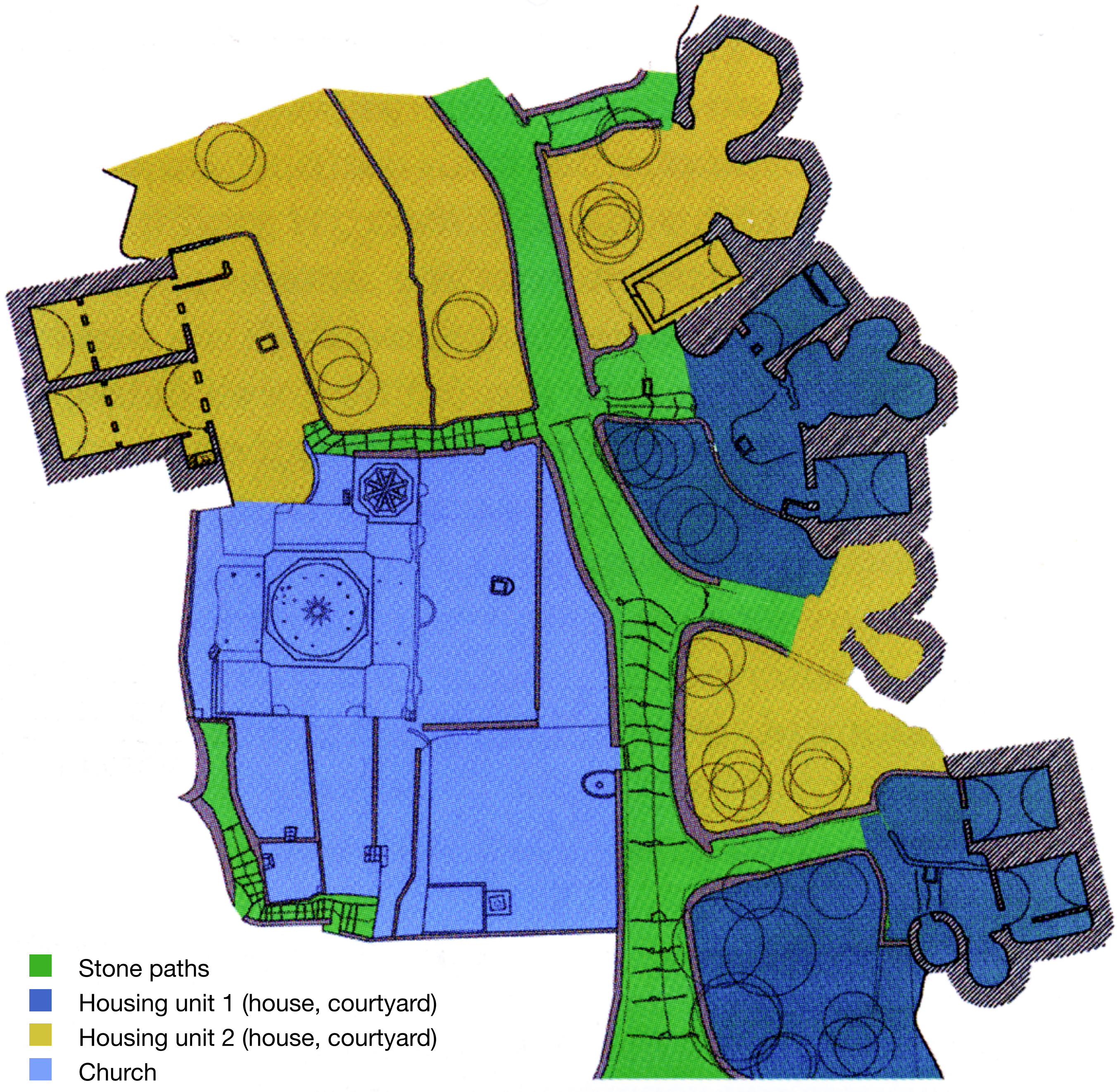


Figure 113. Village taxonomy showing the arrangement of houses around the shared public space and the village church (Palivou & Tzaxili, 2015).

The human scale in Agrilia

As is the case with most vernacular architecture, the architecture of Agrilia is anthropocentric; the dimensions of building units, the height of the walls that line the stone paths conform to the scale of the human body.

But the architecture of Agrilia is not only bound to the human dimension – it is also severely influenced by the morphology of the ground it is built on. The winding stone paths traverse the landscape following the path carved by seasonal gullies. This makes moving around the village disorienting. The large stone walls along the paths that are built to protect the houses and allow for the courtyards to be built on even ground provide limited visibility to pedestrians. However, this limited visibility allows one to see precisely what is needed. Houses have direct visual contact with one another and people walking in the paths are visible only when passing in front of a house. Since life in Agrilia develops around the paths and courtyards, it is important that these are not hidden from plain sight.

Finally, the limited visibility of pedestrians walking along the paths warrants the existence of reference points or architectural elements that aid in people's orientation as they traverse the village. To solve this problem, Agrilia's residents – as did their Theran neighbors – made sure to introduce semi-repetitive elements into the building landscape (Daniil & Zacharatos, 2015). Repetition creates familiarity, and familiarity helps with orientation. Therefore, one finds that, in Agrilia, building units are almost identical and are designed and built around an archetypal idea emerging from the most basic human needs.

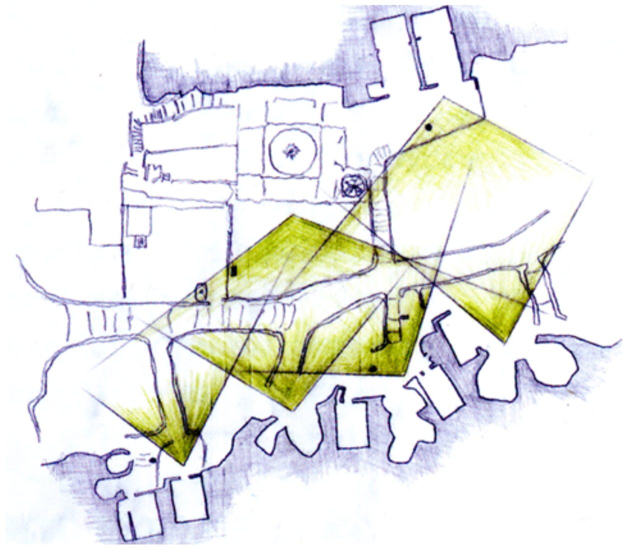


Figure 114. Visual comunication from house to house in Agrilia, top view (Daniil & Zacharatos, 2015).

Figure 116. Impressions of a pedestrian walking along the stone paths in the village (Daniil & Zacharatos, 2015).

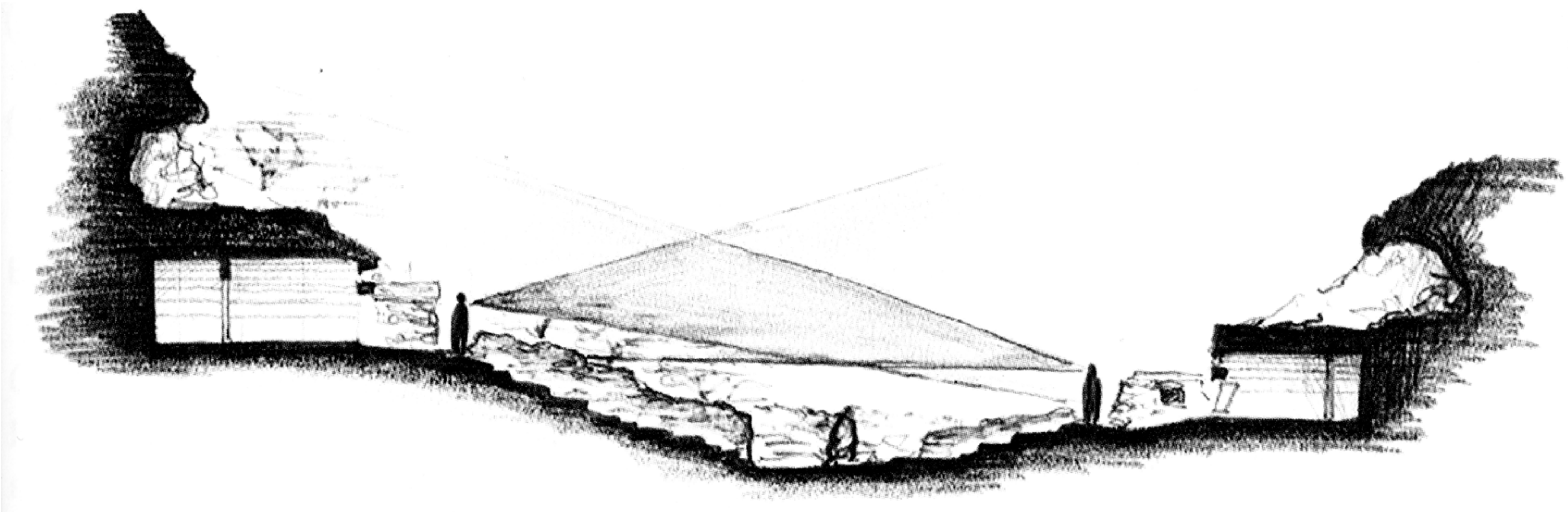


Figure 115. Visual communication from house to house in Agrilia, section drawing (Daniil & Zacharatos, 2015).

Conclusions and design inputs

Once again, we see the architecture of the village shaped by its environment. Warlamis (1995) describes it as a form of *"eco-based vernacular architecture in complete harmony with the environment and elements of nature"*, where every shape and every detail positively encourages and actively relates to life's requirements.

It may seem counterintuitive to design a town where public space is confined to the transitional spaces between private housing units, but when this is dictated by nature, the private turns public, and social life in the village adapts to its new context. The houses, in turn, move many of their amenities outside (with the most notable example of ovens, which were used for communal baking) where they can be shared with neighbors. The Theran house seems to provide the perfect example of an uninterrupted chain reaction with the most basic human need (shelter) as a starting point, and a fully-formed society as an end. From cave to house, to communal space; from precipitation, to ravines, to stone paths and cisterns for water collection.

"Every shape and detail in the Theran house actively relates to life's requirements".

Only, now, the chain reaction has stopped; the environment has taken over and the most basic need is now not to build, but to rebuild. And rebuilding brings forth new requirements. For starters, the architectural indivisibility of Agrilia suggests that an intervention would derive most of its success from its achievement of a complete revival of the village; i.e., the intervention should be applicable to repeating cases of damage, rather than isolated ones.

Fixing multiple cases at once

This input is facilitated by the building typology, which we will discuss next. The repeating architectural features that help people navigate the narrow stone paths of the village make the houses semi-standardized, making their revamping easier, even parametric. Earlier on, when discussing the *LSAM case studies*, we saw that most 3D printing projects make use of parametric geometry control as a 3DP principle, and we concluded that opportunities for added value in preservation could coincide with opportunities for parameterization. This repetition of architectural features provides precisely this kind of opportunity.

Finally, studying the work of Boulouki to understand a traditional approach to preservation, we see that repair and reuse are often exclusive. That is, they do not need to happen at the same time unless the site requires it. However, they are not only exclusive of each other, but also in their approach to preservation; meaning that an intervention often focuses more on what it should not intervent upon rather than what it should. An example of this is the cisterns repaired by Boulouki. The technique used to plaster the walls of the cistern is an extremely specialized plastering technique that makes the walls completely waterproof. In this case, it is the building technique that constitutes a form of heritage and should be preserved, rather than the cistern itself. Thus, the focus of Boulouki's intervention is not the cistern, but the technique; by repairing the cistern, they brought together artisans and construction workers and used the intervention as an opportunity to transfer knowledge from generation to generation.

This exclusivity applies to our intervention as well. As important as it is to fix the damage existent in Agrilia, we must be very careful when deciding what to fix, as we will inevitably be supplanting some technique, material, or both, in order to achieve the intervention. This design input, just like the previous one, relates to the approach of the intervention rather than its actual, physical design, but without a solid, watertight approach, the intervention could miss the point entirely.

What to fix and not to fix

Building typology

At this point, we have established that houses in Agrilia acquire most value when considered a part of a larger whole. However, Santorini's unique landscape has made housing units evolve differently from other forms of folk architecture. This chapter will analyze the unique anatomy and building typology of the Theran house.

Caves as archetypal constructions

Warlamis (1995) describes Santorini's architecture as archetypal because of its practically uninterrupted evolution from cave dwellings to large building complexes that maintain their character throughout all the stages of their development. In order to understand the building typology of the island, we must understand its history. Similarly to how public space in Agrilia is divided according to the morphology of its environment – the steep, narrow cliffs on which it is built – houses in Thirasia and Thira make use of space and are built in ways that are also determined by their environment.

Figure 117. Evolution from cave to house, first steps. Natural caves (top) and first manmade elements (bottom). Images sourced from Warlamis (1995)

"Every element of a Theran house is affected by the house's natural evolution; nothing is superfluous, every detail has precedent."

Architecture in Santorini evolves from natural caves and into modern, fully equipped housing units gradually and organically. In the beginning, there is the natural cave. Subsequently, it is reinforced with a few structural and partitioning elements such as columns, walls, doors, and windows. Still, at this stage it is used for livestock. It is only when the cave is further enhanced that it begins to house people. In fact, it is the application of whitewash (limewash) to the interior and exterior of the cave that it begins to separate from its environment and acquires certain architectural attributes.

In Agrilia, most caves are artificial, meaning they have been carved into the soil by human hands. Caves are domed on the inside because vaulted ceilings support their weight much better and, as houses expand outwards from the cave, they maintain this cylindrical vaulted structure for continuity. In some cases, ceilings are enhanced with cross domes or trapezoid domes but, for the most part, they maintain their archetypal character (Warlamis, 1995). The domes are also reinforced with a layer of mortar and stone to make them more structurally sound and freestanding constructions are built entirely of Theran mortar and volcanic stone. This shape, in combination with the materials used for their construction, has also made them ideal antiseismic constructions.

In the evolution of the cave house one notices that the same elements are added to each house in similar sequences. These include a façade, interior partitioning walls, underground cisterns for the collection of rainwater, furnaces, kitchens, and wine cellars (Filippidis, 1983). This makes each house nearly identical to the one next to it, with their only differences being those dictated by the landscape itself.

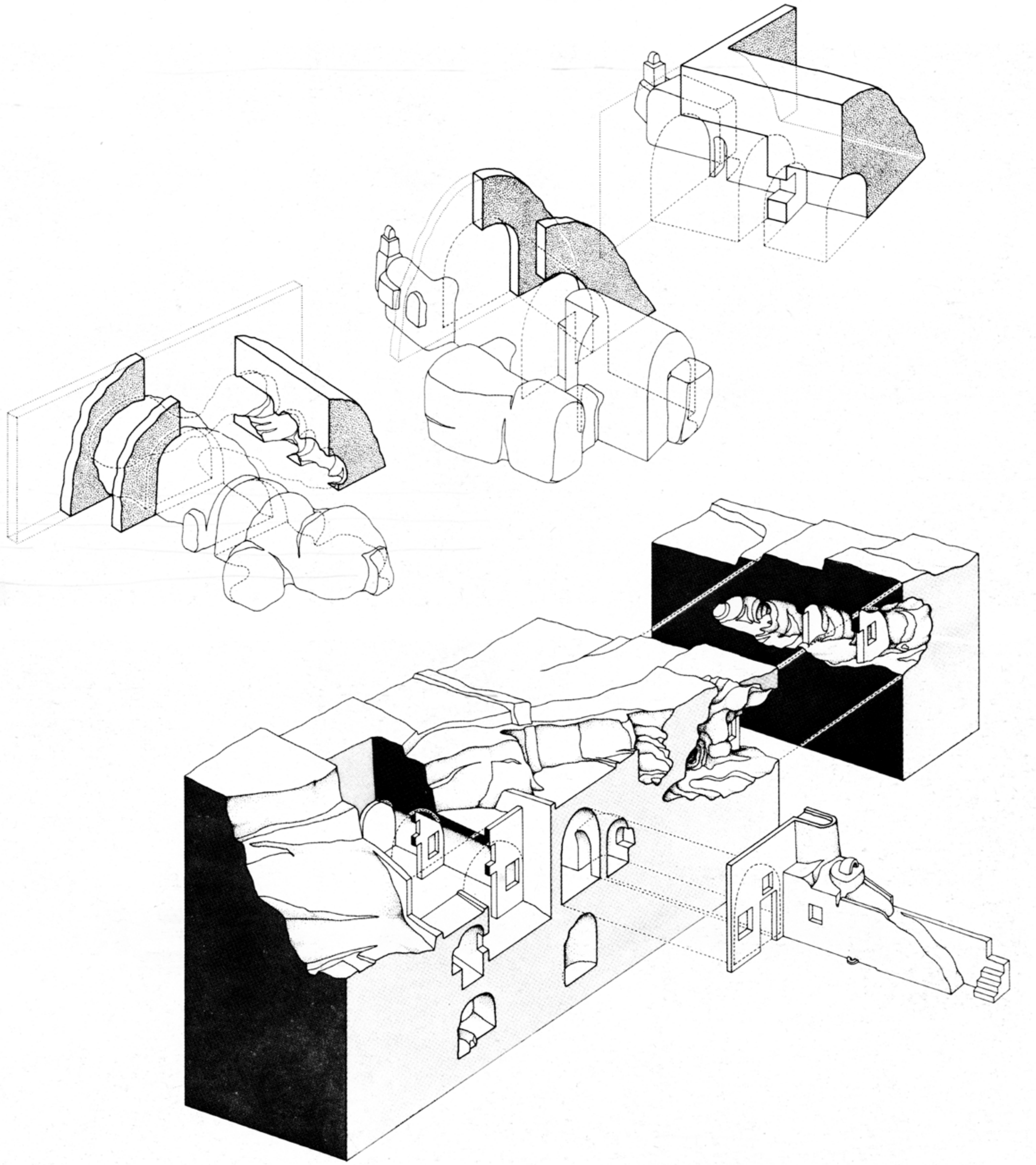


Figure 118. Evolution from cave to house. Drawing sourced from Warlamis (1995)

House typology

Each architectural element is translated from another, making the houses very simple typologically and the transitions between built and natural elements, seamless. Though houses in the main island of Thera expanded over the years into multistoried housing complexes built, by this point, mostly outside the original caves, houses in Agrilia still represent the most basic form of Theran building typology.

The façade is the first fully manmade element to be added to the caves. After it, comes the interior partitioning wall, which is but a spatial translation of the façade, with the only difference being that the leftmost window often transforms into a shelf as the wall is moved inwards. The rest of the elements remain the same and are repeated endlessly across the entire village. All facades are made up of a door, two windows on either side of it for visibility, and one smaller one above it for ventilation.

Two nearly identical spaces make up most housing units. According to Daniil & Zacharatos (2015), one of these traditionally functioned as the main living space, while the other served a secondary purpose – depending on the house, it may have been used as a wine cellar, storage space, stable, or guesthouse.

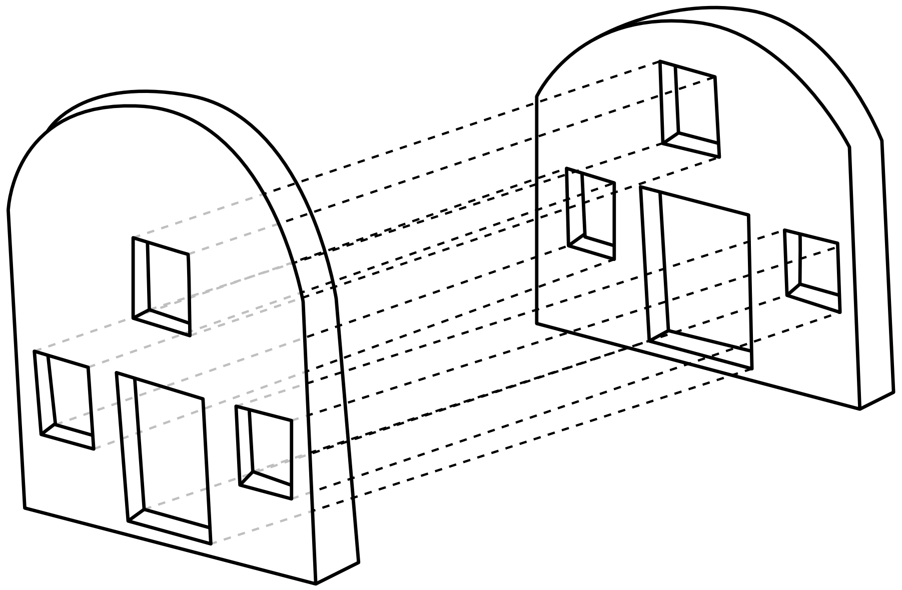


Figure 121. (Opposite top) House no.19 at the entrance of the village. The space on the left functioned as the main house, while the one on the right was used as a secondary living space - a type of guesthouse.

Figure 120. (Opposite bottom) Drawing of facade anatomy.

Figure 119. Facade and interior partitioning wall as a spatial translation of the former.

Materiality

One of the more unique aspects of Agrilia and of vernacular Theran architecture as a whole is its materiality. The traditional materials used, as well as the architectural and building style that evolved out of the progression from cave dwellings to freestanding houses discussed earlier, give Agrilia a unique look and feel that is impossible to replicate elsewhere.

Due to the gradual evolution of craft in the island, the softness of the natural forms dictated by the caves translates to the manmade elements that are added to the houses. Though they are irregularly shaped, the interiors are arranged geometrically; however, in all cases, this geometry is softened by the visual plasticity of the original natural forms.

Agrilia was originally settled because of its proximity to the Theran earth mines on the southern coast of the island. However, Theran earth sourced from the mines was only exported for large engineering projects abroad; the materials used for the reinforcement and enhancement of the caves were those collected during their excavation. The entire island is covered with a thick layer of earth composed of pumice stone, Theran earth (volcanic ash), and volcanic stone (magma residue). Therefore, the excavation of the caves unearthed volumes of material in the form of stones and dust with varied granulometry – from <0,063mm to 32mm (Boulouki, 2022). Thanks to Theran earth being a pozzolan, when mixed with uncarbonated lime - calcium hydroxide - and water, it forms an excellent hydraulic mortar (Gibbons, 1997). This meant that the materials extracted during the excavation of the cave could be used to construct large architectural elements by stacking the stones and using Theran earth as a binding mortar. Additionally, different concentrations of lime and Theran earth produce a variety of materials, from plaster to concrete with pumice aggregates. The materiality of the houses in Thirasia is therefore a translation of the materiality of the landscape.

"The use of local materials with little pre or post-processing give softness to the Theran house, as if it was created by the landscape itself."

Figure 122. Anatomy of partitioning walls, showing the variety of volcanic materials used

When set, Theran mortar has a light grey tone that creates a stark but organic contrast with the deep black – and somewhat less often, red - volcanic stones. The contrast of the landscape is carried over to manmade structures with the introduction of human touch. Stones in Agrilia are not cut or processed in any way, and when used to build walls, they are arranged somewhat haphazardly, resulting in irregular, mosaic-like surfaces.

The monochromatism of building materials in Agrilia make the houses almost minimalistic, were it not for the intricate irregularities of the stone and the morphology of the landscape which dictates much of the buildings' form. Still, chromatically, the only splashes of color come from the rarely used red stone and, in its absence, from the cacti that – at this point in the village's abandonment – threaten to take over the landscape. Houses blend in seamlessly with the landscape and anything that stands out in it is either nature-made or a result of the materiality of the stones and mortar. When designing architectural details, therefore, ornamentality is kept at a minimum.

Finally, it is interesting to note how the current materiality of the village is affected by decay. The gradual abandonment of the village and its exposure to the elements has left them to slowly fall apart, with the first parts of the façade to decay being the layer of plaster spread over the stones. This gives almost every wall in the village – exterior and interior – an intense layering effect that further contributes to the roughness of wall textures and their puzzle-like appearance.

"The materiality of Theran houses is characterized by a textured irregularity - in their building elements, their assembly, and their recent decay."

Figure 123. Interior wall with shelf. Stones around the shelf are arranged almost randomly creating an intricate abstract mosaic.

Figure 124. (Opposite) Details of layering on interior and exterior wall fragments

Conclusions and design inputs

The chain reaction discussed in the previous section extends onto the building typology of houses in Agrilia. The formal translation of architectural features dictates the anatomy of the houses; the facade and interior walls enhance the repetition of features already shown in the village typology, further reinforcing the need for parameterization in the repair of Agrilia.

Every element of the Theran house is the result of a small step in its evolutionary process. Now, with Agrilia being abandoned and the houses in decay, repair and reuse must continue the same ecological process. This gives us a direct input for the design of the intervention: to allow the look and feel of the intervention - its form and materiality - to be directly affected by its environment and how it is made. The next stage in the evolution of the Theran house is its repair; as such, it should contribute to the layering that already exists in Agrilia.

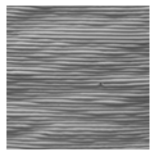
Let the context
dictate the form

The present state of the village in its decay presents an interesting choice in the preservation approach. Part of the uniqueness of Theran architecture lies in its building techniques, which suggests that the preservation of the village should attempt to rebuild the houses as they were as a way to preserve these techniques - just like Boulouki did with their restoration of the paths and cisterns. However, this approach can happen simultaneously with another that highlights the present state of the houses as ruins. We have seen the outermost layer of plaster and limewash on the houses fall and reveal, underneath it, the stone and mortar - the "skeleton" of the house. By keeping the houses partly in their decayed state, we allow their underlying structure to show, highlighting the genius of Theran vernacular craft not by emulating it, but by preserving it in its original form.

"An intervention that shows the houses in their present state of decay could highlight the genius of Theran vernacular craftsmanship."

Figure 125. Inside a Theran house, the lack of plaster and limewash reveal the secret to unreinforced domes: Theran mortar.

If carried out following this line of thinking, the intervention should contribute to the layering of the site. However, to achieve harmony and continuity, we can develop our own artistic approach to the materiality of the intervention. 3D printing gives us the ability to manipulate the objects we produce in a microscopic manner, generating patterns and textures in their surface without affecting their overall form. Combining this with a local material could achieve continuity in the materiality of the intervention while using a principle unique to 3D printing to develop our own stylistic approach that makes the intervention unique.



Artistic expression
through 3DP principles

Traditional materials and building techniques

Upon studying the building typology of Theran houses and their materiality, it becomes clear that their uniqueness comes largely from the materials used and the traditional techniques through which they are processed. As we discussed above, not much is added to the raw materials – Theran earth is merely mixed with lime and water, and volcanic stones are very rarely processed or cut.

Discussions with experts in preservation and the two visits during which the above analysis took place outlined the importance of craft in preservation. While it is interesting and, ultimately, useful to introduce modern techniques and materials into the adaptive reuse of historic architectural works, these are to work in tandem with existing vernacular techniques – especially when these techniques play such an important role in why the site is culturally significant and worth preserving. Therefore, this section on the traditional building techniques used in Thirasia is included here not only as inspiration for the intervention design, but also to gain an understanding of the strengths and weaknesses of traditional techniques, so as to introduce LSAM where it truly fits and not to displace craft where it need not be displaced.

Figure 126. A thick layer of volcanic ash and stone covers the entire island, making the sourcing of materials for building possible directly on site.

Theran earth and stone

Theran earth – or, as the locals call it, aspa (άσπα) – is a type of pozzolan with excellent hydraulic properties. The term pozzolan refers to siliceous or siliceous-aluminous materials, either natural or artificial which, while not exhibiting cementitious (i.e., binding) properties in their ordinary state, form hydraulic compounds when finely ground and mixed with hydrated lime in the presence of moisture (Boulouki, 2022). Being a pozzolan, Theran earth's properties are enhanced in the presence of moisture, making it ideal for use in humid environments, as its resilience is continuously improved over time. Furthermore, when used with aggregates – specifically pumice stone – it makes for an incredibly light form of concrete which can be used to create vaults of up to 4m in diameter without the use of rebar or reinforcement of any kind (Filippidis, 1983). The islands that make up Santorini do not have forests; therefore, wood was always scarce in the archipelago and Theran earth's properties allowed people to build without it.

Aspa can be used in concrete, mortar, or plaster, just like cement. This makes it a versatile building material and, in Theran vernacular architecture, it is used as all three. Concrete for the crafting of domes and columns; mortar for binding stones to build walls and other architectural elements, as well as bricks; and plaster to coat interior and exterior surfaces and apply whitewash for increased durability.

What is particularly interesting about the use of Theran earth in Agrilia is the scarcity of bricks made of Theran earth. While there are examples that can still be found among the ruins and all evidence points to them being a convenient building material due to its lightness, they were seemingly not used much, likely because precisely designed building elements such as bricks were not needed due to the versatility of Theran mortar. However, when it comes to the reconstruction of the village, more attention to detail and precision is needed to repair and adapt the ruins. This signals towards a reintroduction of the Theran earth brick as a building element into the architectural makeup of Agrilia.

Figure 127. Rectangular brick made of Theran mortar with pumice stone aggregates

Figure 128. (Opposite) Interior wall built with black volcanic stone and mortar, transitioning to Theran concrete with pumice stone aggregates for the vaulted ceiling, due to its low weight.

"The reconstruction of Agrilia requires a more measured approach that warrants the reintroduction of the Theran earth brick."

Theran earth's binding qualities also indirectly affect the materiality of the site. According to Filippidis (1983), stones were traditionally not processed or cut because Theran mortar is such an excellent binding agent that it did not require great attention to detail when stacking the stones, resulting in the irregular textures discussed before. Testimony gathered from local builders by Boulouki (2022) verifies this:

"We built with stones and mud (aspa); we didn't place the stones vertically—there was no issue about how the stone would fit [...] You'd stick the stone in place, and the gaps it left, because they weren't squared, were filled with mud. We placed the stones however they fit because the stones of Santorini aren't square—we didn't chisel them."

Lastly, it was mentioned earlier that Theran earth can be ground to very fine particles - <0,063mm – and its use as concrete and mortar to make bricks verifies its use as a castable material; i.e., it can be poured into casts or molds. Laboratory research by Boulouki (2022) highlights the similarities in its behavior with Portland cement and, upon further consultation with material experts from the organization, it was asserted that the material is likely pumpable and, therefore, can be printed with. Granted, its printing behavior is still to be assessed, but all evidence points to it being used in a 3D-printed intervention.

"Laboratory research by Boulouki suggests Theran mortar can be pumped and extruder, making it a suitable candidate for 3D printing."

Integrated elements

The plasticity of Theran earth and the forms that result from its shaping, as well as its binding properties, allow it to integrate a variety of elements – decorative and functional. Though houses in Agrilia contain only the bare essentials and are typically not adorned with ornamental features, these bare essentials are organically integrated into the fabric of the house. Even the house itself is integrated in the landscape, as it is usually carved out of the hillside.

The inside of Theran houses contains a mix of tectonic and stereotomic elements – some built by addition of material, some by removal. Shelves are carved directly into the wall and windows fit into large gaps in the façade. The smaller gaps in between these elements and the building envelope are filled in with mortar, just like the gaps between the uneven stones are when building the walls themselves.

Furthermore, superficial layers of Theran plaster – a mixture made with a higher percentage of lime than Theran mortar – can be worked similarly to gypsum, with skilled craftsmen carving simple decorative details out of them. Examples of this were observed in the light fixtures and window frames, among others.

Both the integration of support elements, as well as decorative or design features can be linked directly to two LSAM features identified in the case studies. This creates an opportunity for LSAM to be integrated harmoniously into the architectural makeup of the village. In fact, a single 3D-printed element could feature both decorative details, as well as integrate structural or support elements, making such an intervention achieve repair and reuse simultaneously.

Figure 129. Window and shelf inside a house in Agrilia carved out of the building fabric.

Figure 130. Light fixture and window details, showing the versatile plasticity of Theran earth when mixed with different quantities of lime.

Conclusions and design inputs

The importance of craft as a form of heritage should not be underestimated in the case of Agrilia. The rural exodus that decimated the population of the village coincided with the export of Theran craft to the places where the villagers emigrated - mainly the industrial hubs of Piraeus and Laurion. The workers took with them their knowledge and skill, but these worked in tandem with the local Theran materials, which could not be exported. The revamping of Agrilia provides an opportunity for the return of craft to the island.

Traditional house of the future, the sole example of LSAM in Adaptive Reuse analyzed in *Part II,* highlights the similarities between traditional craft and digital fabrication: *"Working with robots and working with traditional craftsmen are similar methods, as there is no need for drawings - robots operate based on code, and craftsmen learn from mock-up models and adapt on site"* (Ratoi & Lin, 2023). An intervention that does not displace craft, allowing craftsmen and robots to work together, could turn the spotlight on Agrilia; and a participatory project similar to those carried out by Boulouki would not only educate young craftsmen on traditional techniques, but also on cutting-edge ones like Large-Scale AM, materializing the concept of the new master builder that we introduced in *Part I*.

Combining craft:
digital and artisanal

The reintroduction of the brick as a building element in Agrilia also provides a convenient opportunity for the project. Bricks were rarely used in Thirasia because of the versatility of Theran mortar in combination with uncut stone. However, repairing the damage present the houses requires a greater degree of precision and personalization. This opens the door for both the brick as an architectural element and 3D printing as a technology capable of producing bespoke geometries at scale. Earlier on, in the *LSAM case studies,* we saw the versatility that LSAM provides to a project in terms of scale, depending on the material used, the intervention site, and the machine. The narrow stone paths and overgrown foliage, as well as the condition of the caves do not allow for a large machine to be used on site. An intervention in Agrilia could therefore be printed close to the site and transported to it, meaning that the smaller the individual elements that make up the final piece, the easier their production and transport would be. This points us towards an assemblable intervention composed of bricks or tiles, rather than a single-piece one. Furthermore, since tiles or bricks would have to be held together somehow, this could be achieved either with an LSAM feature - interlocking components -, or by using Theran mortar as a binder - thereby creating work for local craftsmen in the assembly of the tiles.

Dividing the design
into tiles or bricks

As the intervention comes together through these design inputs, we can draw more parallels between traditional techniques in Thirasia and Additive Manufacturing. The power of AM is expressed through the intervention by creating additional value, but also by preserving some of the value inherent in the qualities of the site. Continuing the evolution of the Theran house and its building techniques, some of its aspects must be translated into the present. Just as the vaulted ceilings of the caves were maintained as the houses extended outwards, we must identify the strengths inherent in Theran building practices and attempt to translate them to the 3D printing realm.

> *"The revamping of Agrilia with 3DP presents an opportunity for the return of craft to the island and the training of the new master builders."*

The first and easiest translation is achieved through the material. Theran earth is clearly the greatest enabler of Theran architecture and its most representative element - both because of its properties and its materiality. It is subtractively sourced *in situ* and transformed additively into a habitable housing unit. It allows for the construction of domed houses without reinforcement and is used as concrete, mortar, and plaster. It makes the houses blend in with the landscape while allowing for the carving of decorative elements in the facades. All in all, Theran earth is by far the ultimate expression of the island's architecture. The conclusion from Boulouki's research suggest pumpability and extrudability, leading one to assume that it might be used in 3D printing. If this were proved possible, it would attribute great value to the intervention.

Printing with
local materials

Theran earth owes much of its power to its lightness, which it achieves thanks to its high content of pumice stone. When used as concrete, pumice stone and black volcanic stone were used as aggregates. As the height of the house increased relative to the ground, more pumice stone was added to the mix to make it lighter. Here, we can draw a parallel with the LSAM feature of *gradient material properties*. AM allows the manipulation of complex parametric geometries. Using the height of a piece relative to the ground, an infill gradient could be created to make the top pieces lighter than the bottom ones, harnessing the power of pumice concrete without using aggregates (since, incidentally, printing with aggregates would provide an added challenge due to their abrasiveness and size, which makes them difficult to pump and extrude).

Infill gradient
relative to height

Finally, the integration of support and decorative elements in Theran houses directly relates to two LSAM features: *integrated support elements* and *integrated design elements*. Depending on the chosen case of damage and if there are support elements or design elements that need to be integrated into the printed pieces, a 3D-printed design should put special emphasis on this integration.

Integrating elements:
support and design

Intervention design

Earlier in the project, we analyzed a series of case studies on Adaptive Reuse to get an idea of the different approaches architects and designers have taken to preservation. We saw that, depending on the case – its proposed new use, the type of ruins and their significance, and the condition of the preexisting building fabric -, approaches varied wildly. This led to the conclusion that, although we can base our intervention on fulfilling the theoretical criteria that affect the success of an AR project, the site itself ultimately will determine the intervention approach. A thorough analysis on the site's heritage will reveal what can and should be preserved, and will largely guide us in the design process.

Having analyzed Agrilia - its cultural background, its typology, and its local materials and building practices - we can now proceed to integrate all of our conclusions and design inputs into one focalized intervention. This section first detail the choice of damage upon which to intervene, before moving on to the design of the actual intervention and all its characteristics.

Agrilia's cultural significance

Any heritage site's cultural significance is dictated by a variety of factors. Depending on the case, these can be historical, architectural, social, or otherwise. When it comes to preserving the site, they must first be clearly identified in order to choose an intervention approach. A designer must know what to highlight, what to integrate into their design, and what to leave behind to make space for the new use.

"A designer must know what to highlight, what to integrate into their design, and what to leave behind to make space for the site's new use."

In the case of Agrilia, the organization in charge of the current restoration effort aimed at preserving the site is Boulouki, and their research points to the houses having to be revamped to meet modern standards of living, while preserving as much of their character as possible. Their approach to preservation centers around vernacular building techniques – reviving these traditional techniques by passing knowledge down to young craftsmen in the island. Aside from this, however, there are a few other aspects of the site that make it unique and worth preserving.

Building techniques

Traditional building techniques, specifically those that involve local materials are what give Agrilia its unique form and materiality. An intervention in Agrilia will have to respect the preexisting building fabric where it is not damaged, as well as leave space for traditional techniques to be applied in restoration. This is especially important because of the broader context of which Agrilia and Thirasia are a part; the advent of tourism and its gradual overtaking of neighboring Thira (Santorini's main island) has incited developers to build cheap and fast, rendering Theran architecture kitsch and performative. Since tourism has not spilled over to Thirasia just yet, there is an opportunity, here, to rectify its neighbor's mistakes and contribute to the sustainable development of the island.

Materials

Traditional materials, especially Theran earth due to its versatility and historical significance, are perhaps Santorini's most unique form of tangible heritage. Theran mortar's excellent mechanical properties and potential for use in LSAM beg for its utilization in a 3D-printed intervention in the village.

Village typology

Some aspects of the *village typology*, namely its use of public space and its indivisibility are important to preserve. While revamped houses in Agrilia will not be used in the same way as traditional houses were – eliminating the need for stables or wine cellars -, the way the village is built was largely dictated by the environment. The ecological model of Theran houses must therefore be continued by preserving these aspects of their typology. Especially the village's use of walking paths and semi-private courtyards as shared public space, seeing as these contribute to the village's indivisibility as a coherent whole. This points, specifically, to any intervention's power lying in its ability to be extrapolated to the entire village. Achieving a simultaneous revamping of the village in its entirety is imperative since, as was seen previously in the analysis section, houses in Santorini cannot be considered as autonomous building units, but rather part of an indivisible whole.

Building typology

Agrilia's *building style and typology* are also the result of a natural progression. Its preservation therefore ensures the preservation of this sustainable approach to architecture and construction. Theran house typology is a result of the environmental factors of the island; as such, it is perfectly adapted to the island's morphology and climate. Furthermore, the archetypal look of the houses is regarded in literature as inextricable from their cultural and architectural significance (Filippidis, 1983; Boulouki, 2022; Douskos, 2015; Palivou & Tzaxili, 2015; Warlamis, 1995). So, while revamped houses will not feature the same amenities as the original ones – they will exclude wine cellars, stables, and traditional coal stoves, among other things – their innate typological characteristics – as they were described in previous sections – must remain intact.

Opportunities for value creation through LSAM in Agrilia

Following the conclusions of our analysis, we are able to identify opportunities for value creation in Agrilia. The final intervention was the result of an iterative process guided by the design tool created at the end of *Part II*. This tool provided a base upon which to build the design by breaking it down into LSAM-enabled features.

While some of these features proved to be niche features difficult to apply generically to any site, others stood out already in the first visit to the island. Light scattering, visibility, shading, evaporative cooling, ventilation, biomimicry, and sound diffusion could not be found to apply to the site. Though at first, the human scale in Agrilia and visual communication within the village appeared to signal towards the potential integration of visibility screens in the facades of the houses, upon consulting literature on the matter, it was clear that visual communication in the village is already achieved by the orientations of the houses and the morphology of the landscape, and it does not need to be tampered with. The same was true for the other features: the ravines in Agrilia have excellent acoustics; the houses have windows for ventilation that are inherent in their typology; they do not have problems with heat stress, as the interior of the caves is always cool; light inside the houses is sometimes scarce, but the small interior spaces are usually well-lit; and nature does not seem to have a problem thriving among the ruins, making biomimetic designs to attract biodiversity seem superfluous.

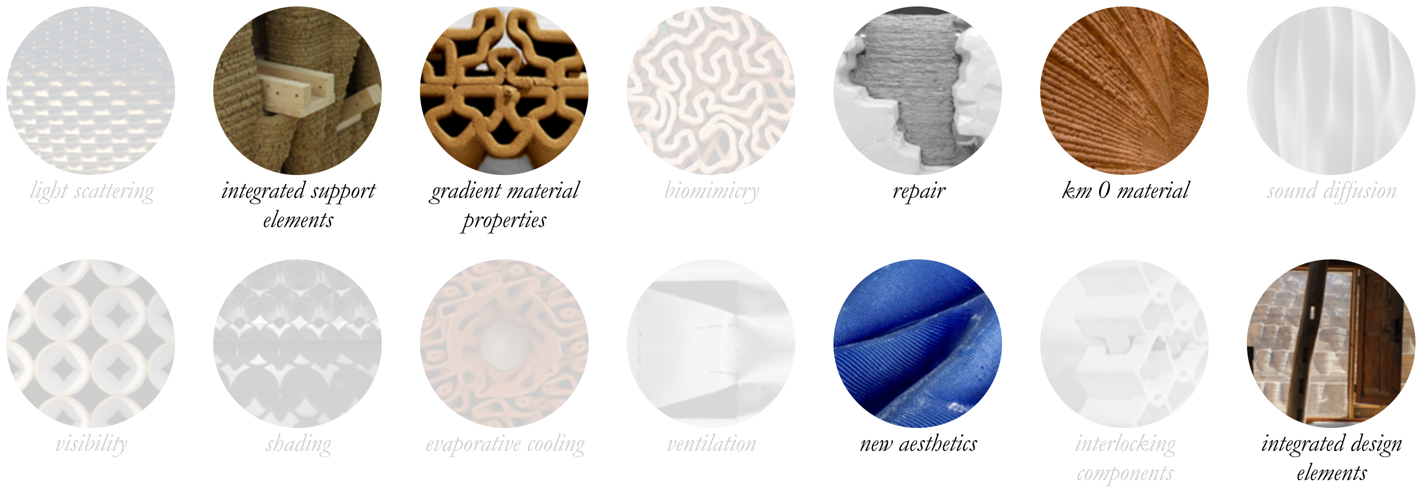


Figure 131. LSAM features with identified potential for added value creation if used in Agrilia

At the same time, six features stood out as offering potential solutions to the revamping of Agrilia:

Integrated support & design elements. The aforementioned versatility of Theran earth as plaster, mortar, and concrete allowed for the integration of architectural features directly onto the fabric of the caves. LSAM offers the same versatility not only through the printing of Theran mortar, but also through parametric geometry control.

Gradient material properties. Variable infill printing as used in the LSAM case studies achieved lighter and heavier sections in the same printed object. Drawing a parallel between the use of pumice stones as bricks and/or aggregates in domed constructions in Agrilia, a 3D-printed intervention could be introduced with the same benefits (no need for rebar or reinforcement of any kind).

Km 0 material. Assuming the printability of Theran mortar as a paste-like material, its use in a 3D-printed intervention is a given.

Repair. Seeing as the houses in Agrilia featured many wall gaps and large volumetric losses, it is likely that an intervention that simultaneously achieves repair and reuse will have to physically repair some of the damaged fragments. By generating toolpaths from 3D scans and printing smaller elements off site, this seems feasible.

New aesthetics. Inevitably, a 3D-printed intervention will have to strike an aesthetic harmony between 3DP and the materiality of Theran houses.

Choosing cases of damage

The design inputs extracted from the analysis first helped choose a case of damage upon which to intervene. The indivisibility of the village suggested looking for repeating architectural features and cases of damage as potential suitors.

Fixing multiple cases at once

Repetition of architectural features

Aside from the LSAM features that could be integrated through 3DP into Agrilia's houses, finding a case of damage upon which to intervene came down to an intersection between the needs of the village and one of the strengths of Large-scale AM.

Considering the village as an indivisible whole, an intervention in one of the houses would have implications for the rest of them. Simultaneously, 3D printing has the benefit of being able to produce bespoke pieces with the same cost and time efficiency as it would identical ones. Given that houses in Agrilia are nearly identical and they have a number of repeating architectural features, repairing one of them would mean that it is possible – through parametric design and Additive Manufacturing – to repair all of them. If all the houses were truly standardized and identical, the same solution could be achieved with a mold. However, the human error inherent in traditional craft, as well as the irregular morphology of the landscape, make the houses semi-standardized. That is, very similar but, when it comes to the details, varying slightly.

Figure 132. Repeating architectural features in Theran houses as observed in the case of Agrilia.

This repetition of features provides an opportunity for parameterization. However, for this solution to truly fit, not only does the feature need to repeat itself, but also the type of damage. Furthermore, different architectural features allow for more or less LSAM features to be integrated into the design of the intervention. Therefore, the integration of support elements, gradient material properties, and the rest of applicable features were weighed when choosing a case of damage.

Window gaps as cases of damage

Across approximately 130 abandoned houses in Agrilia (Boulouki, 2022), at least 50 of them have intact facades and/or interior partitioning walls. Each of these has two large windows on either side of the door and one above. This makes window gaps the most frequently recurring architectural feature and case of damage.

Windows are also one of the features with integrated additional elements that were identified in the Traditional materials and building techniques section – both because of their integration of wooden window frames as well as carved decorative details in the outermost layer of plaster.

By repairing damaged windows, a solution applicable to multiple cases of damage can be attempted, trying to ensure the survival of the village as a whole. At the same time, six LSAM features can be integrated into its design, drawing parallels between the intervention and the traditional building techniques of Santorini. With a focalized intervention like this one, village and building typology are left intact and, finally, the materiality of the houses is also preserved and layered upon by using Theran earth as a printing material.

What to fix and not to fix

Printing with local materials

Integrating elements: support and design

Fixing multiple cases at once

Figure 133. Window gap in a Theran house in Agrilia, still preserving some of its decorative details.

Figure 134. Intact window in Agrilia, showing the complete decorative frame around the window, as well as the wooden lintel as an integrated support element.

3D-printed architraves

The window gaps observed in Agrilia are not only missing the window and window frame, but the part of the wall that holds the frame in place – the architrave.

The window frames are always made of wood and more often than not have standard dimensions. By keeping this part of the window constant, we can design an architrave that adapts to the gap in the wall while integrating the frame as a support element.

The intervention proposed here is the printing of these architraves in tiles split according to the traditional anatomy of a window and integrating all the aforementioned LSAM features that add value to the intervention, while taking care to preserve Agrilia's cultural heritage in the ways that are outlined in the previous sections. The tiling of the window will make it easier to print and assemble, and will allow for a better integration of the frame. It also allows for tiles to be printed with varying infills and for craftsmen to become involved in their assembly.

Dividing the design
into tiles or bricks

Infill gradient
relative to height

Integrating elements:
support and design

Combining craft:
digital and artisanal

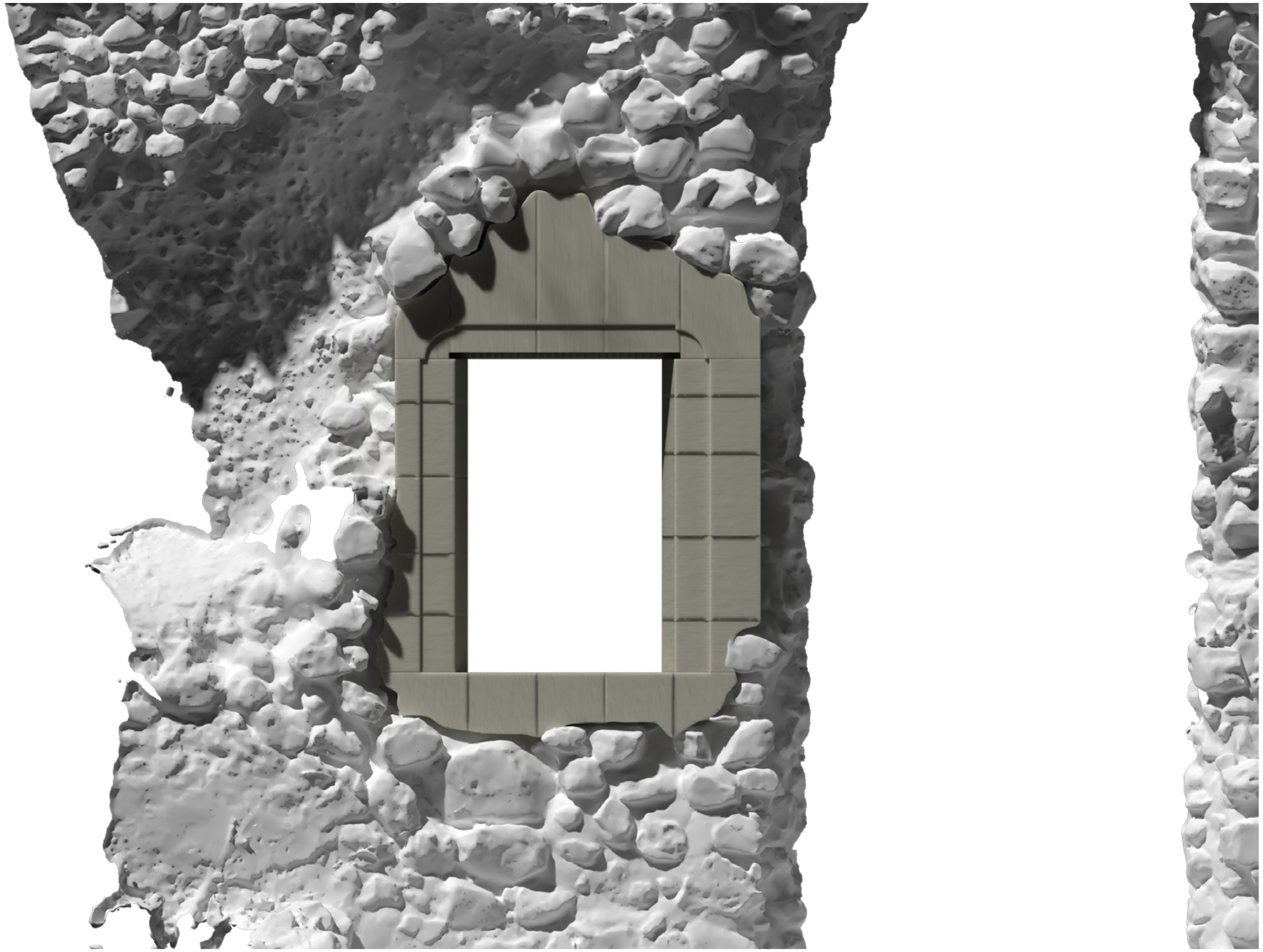
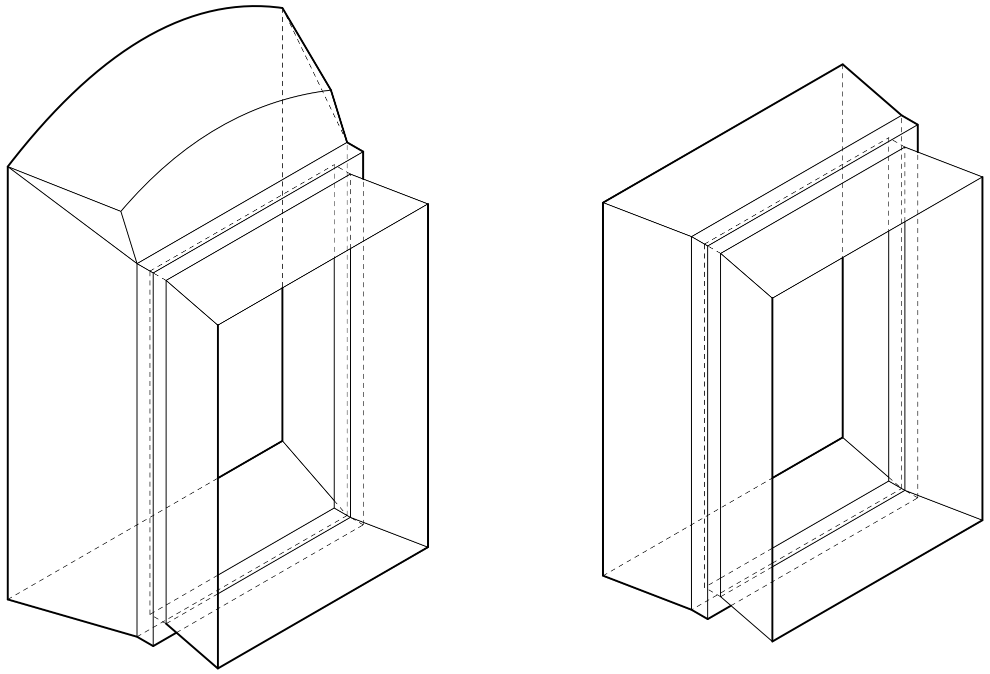


Figure 135. Rendering of the proposed intervention

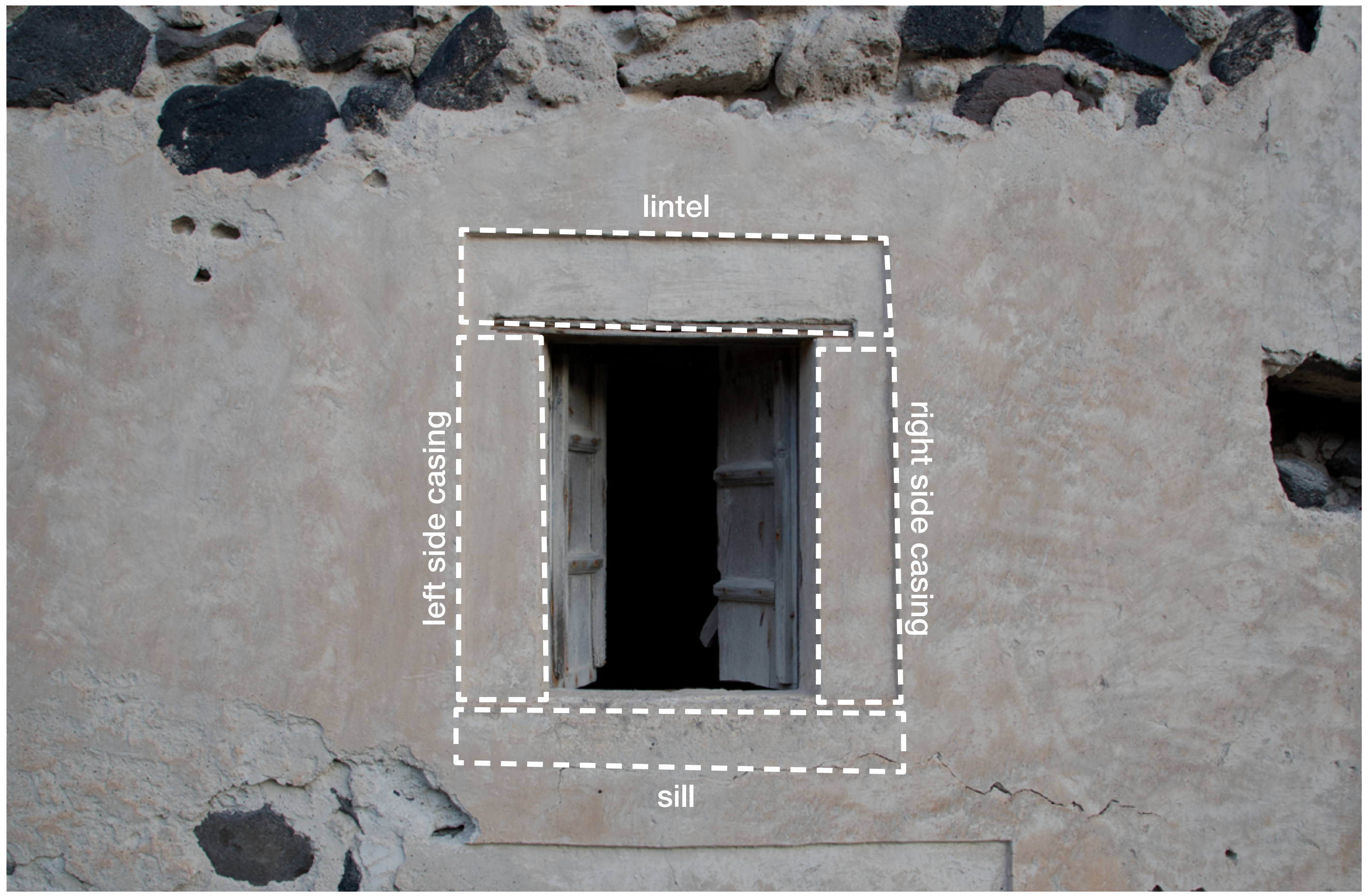


Type A
(domed on the inside)

Type B
(square on the inside)

Figure 137. Window types as observed in Agrilia.

Figure 136. Simplified anatomy of a Theran window architrave.



Anatomy of a Theran window

Window architraves in vernacular architecture are made up of three distinct parts split according to their position relative to the window frame: at the bottom is the window sill; on either side of it, the side casings or jambs; and at the top, the lintel.

Lintels are responsible for holding the weight of the material directly above the window, and therefore should be designed with more caution. Lintels in Santorini are typically made from one large rectangular stone, a collection of smaller stones, bound by mortar, or a large piece of wood. In the case of small stones, it is usually reinforced with a thin piece of wood that distributes the weight of the lintel across the left and right casings.

Windows in Agrilia fall into one of two distinct typologies, as shown here. In one case, the window opening is almost symmetrical, square on both sides and, in the other, it is square on the outside and domed on the inside. Those in larger caves with thicker walls tend to be domed, while smaller caves with thinner walls can only afford square windows (Filippidis, 1983). Additionally, the window frame is sandwiched between the inside and outside openings; it is visible from the inside and invisible from the outside, leading one to believe it must be installed from the inside. Knowing the precise dimensions and typology of these windows allows for a design to be created, adapting to the gap in the wall.

Let the context
dictate the form

Chosen window

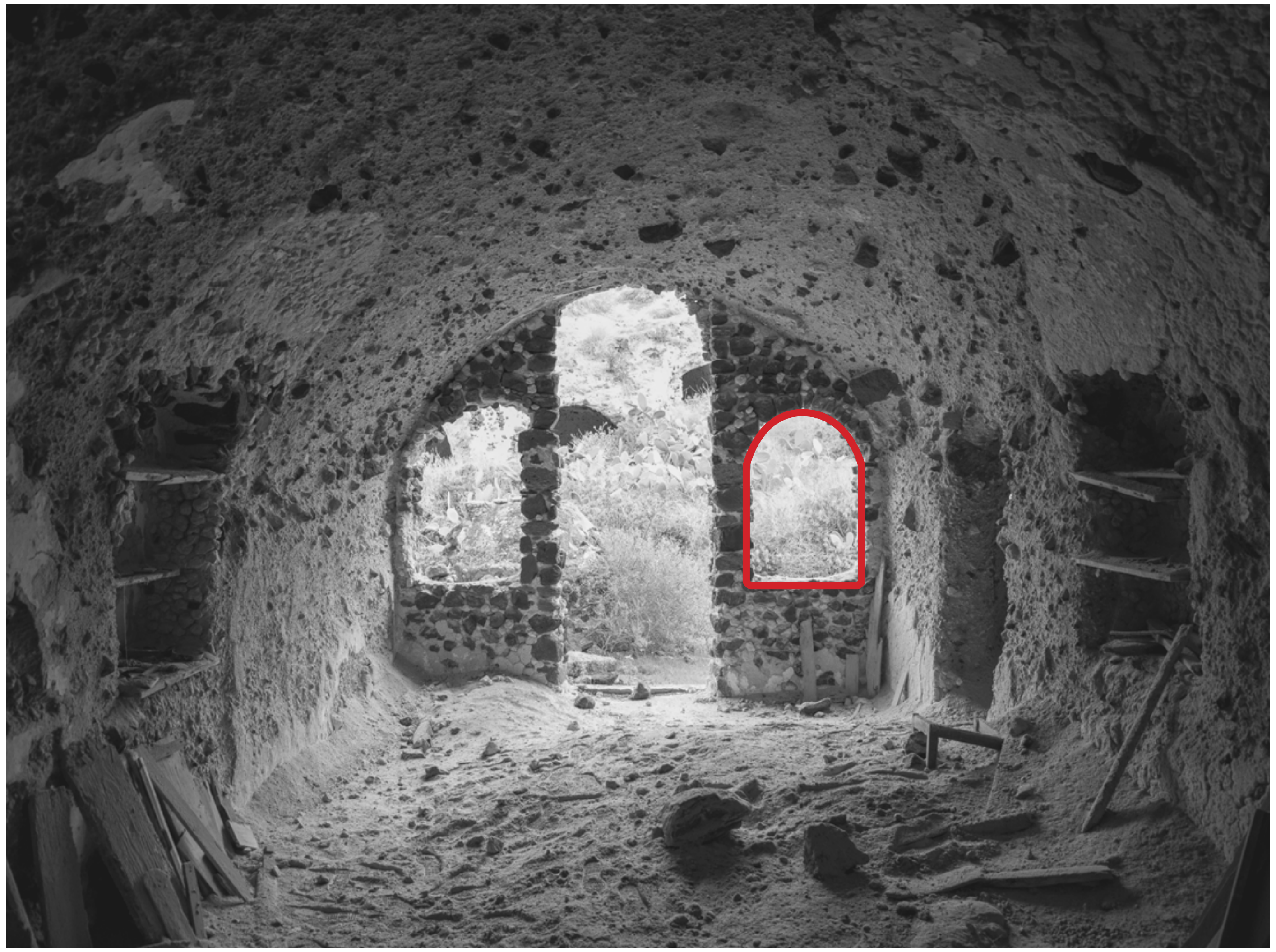
In order to carry out the design and prototyping of this intervention, one specific window was chosen, scanned, and designed for. This is the case of the eastmost window in house no.37.

The gap was chosen because of the following factors:

- The *condition of the gap*. It had a relatively smooth shape and no loose rocks around it that could fall while measuring and scanning it.
- The *lighting conditions*. 3D scanning requires the the subject to be lit with plenty of indirect sunlight. That is, it must be lit evenly and brightly.
- The *accessibility of the house*. Many of the houses in the village, though accessible, had a lot of overgrowth around them that obstructed visibility and would interfere with the scanning process.

Figure 139. (Opposite) House no.37 in context. Located on the SW slope of the ravine, it sits in the shade most of the day and is exposed enough to receive plenty of indirect light

Figure 138. Chosen window for design and prototyping of the intervention, as seen from the inside of the house.



Project approach

The printing of architraves as an intervention in Agrilia was arrived at through a careful analysis of the cultural significance of the village; identifying what makes it worth preserving, what any preservation effort would need to strive for, and connecting all this with the opportunities provided by Large-scale AM.

The preservation of some of the village's characteristics is achieved by omission: by intervening on a small architectural feature and not proposing a large, invasive intervention, the building typology is left untouched, and room is made for traditional techniques to be used in its restoration - after all, 3D printing is meant to be used as a tool in preservation without taking over the entire process.

Preservation is therefore partly achieved passively. Now, having chosen window architraves as the object of the intervention, the value of said intervention must be assessed. Given the particularities of the village – its architectural and building typology, its materials and building techniques, and its cases of damage – the value of the intervention is derived from its adaptability to multiple cases of damage throughout the village through parameterization, as well as its integration of LSAM features, as they were identified in the Opportunities for value creation through LSAM in Agrilia section.

At this juncture, and due to the time and feasibility constraints of the project, the focus turned to the integration of the identified LSAM features, leaving out the parameterization of the intervention. Rather than focusing on writing a parametric script with 3D-scanned meshes as input and printable tiles as an output, the approach taken for this last part of the project was to delve into the integration of the features as sources of additional value, using the window from house no.37 as a case study.

> *"The project's approach focuses on integrating the identified LSAM features into a proof of concept physical prototype."*

Design and prototyping

The design of the printed architrave was carried out according to the limitations and opportunities offered by 3D printing. While some of the design choices required prototyping for their validation, others were simply dictated by the limitations of the technology.

The following sections are broken down into the main principles that either enable the intervention or contribute to its creation of additional value.

Toolpath generation from 3D scans

Sara Codarin's Robotic Restoration PhD thesis showed that repairing wall gaps with on-site printing posed significant challenges due to the collapse of layers under large amounts of material and the narrow reach of the robot arm. For the intervention in Agrilia, these problems were tackled by splitting the architrave into tiles and printing them on site but not directly onto the ruins. This also eliminated the challenge of printing on uneven surfaces, as all the tiles have at least one flat surface that can be used as a printing base.

While toolpaths were therefore not directly mapped onto a 3D scan, they were generated from one. This section briefly outlines the 3D scanning and model generation process.

Dividing the design
into tiles or bricks

Figure 140. Lighting and accessibility conditions of the house

3D Scanning process

The 3D scan of the window gap in house no.37 was made using photogrammetry. Photogrammetric scans are produced by extracting reliable measurements from a set of photographs of a subject. To this end, the window gap was scanned by photographing it from a variety of angles and processing the images taken with a dedicated photogrammetry software (Agisoft Metashape).

Scanning setup

A total of 200 images were taken of the window gap from the inside and outside of the cave. These were divided into three sets:

1. 

Photographs of the entire gap, from a distance of about 1.5m. These were taken from three different heights and fifteen positions that revolved around the gap.

Figure 141. Picture of entire gap

2. 

Photographs of the gap in context. Though these were not necessary to produce an accurate scan, they help the program estimate the position of the other images.

Figure 142. Picture of context

3. 

Photographs of details. These are close-up photographs of details in the gap that were not visible from any of the other angles. They were taken selectively, ensuring that the same detail was visible from at least two pictures, since the program would not be able to accurately locate them otherwise.

Figure 143. Picture of gap detail

The photographs were taken with a Canon 6D Mkii and a 24-105mm lens, maintaining a constant focal length (24mm), aperture (f8), and ISO (400) across the entire set of images and only changing the shutter speed to control exposure, as per Metashape's requirements.

Processing of the 3D scan

The images taken at the site were processed in Photoshop to ensure that exposure, white balance, and sharpness are uniform across all subsets. Though the house was chosen because of its lighting conditions, the images from inside the cave featured dramatically different lighting from those taken from the outside.

Upon importing the processed images into Metashape, a series of operations are carried out to: (1) filter the images based on the program's ability to accurately align them in 3D space; (2) crop the sections of the images relevant to the scan, which also helps with image alignment; (3) align the images and produce a sparse point cloud, i.e., an estimation of the 3D object by points; (4) refine the point cloud and condensing it into a dense point cloud; and (5) generate a 3D mesh out of the dense cloud.

Due to the disparity of the lighting conditions inside and outside the house, the images were split into inside and outside "chunks", and the above operations were done twice. Finally, using 3D markers, the two "chunks" were aligned and the model refined, producing a complete 3D mesh of the window gap.

The mesh generated was smoothened and its polygon count reduced to make it easier to work with – the original mesh featured over 10M polygons, making it very computationally heavy and almost impossible to process further. Finally, the smoothened and reduced mesh was exported and all further design operations were done in Rhinoceros 3D.

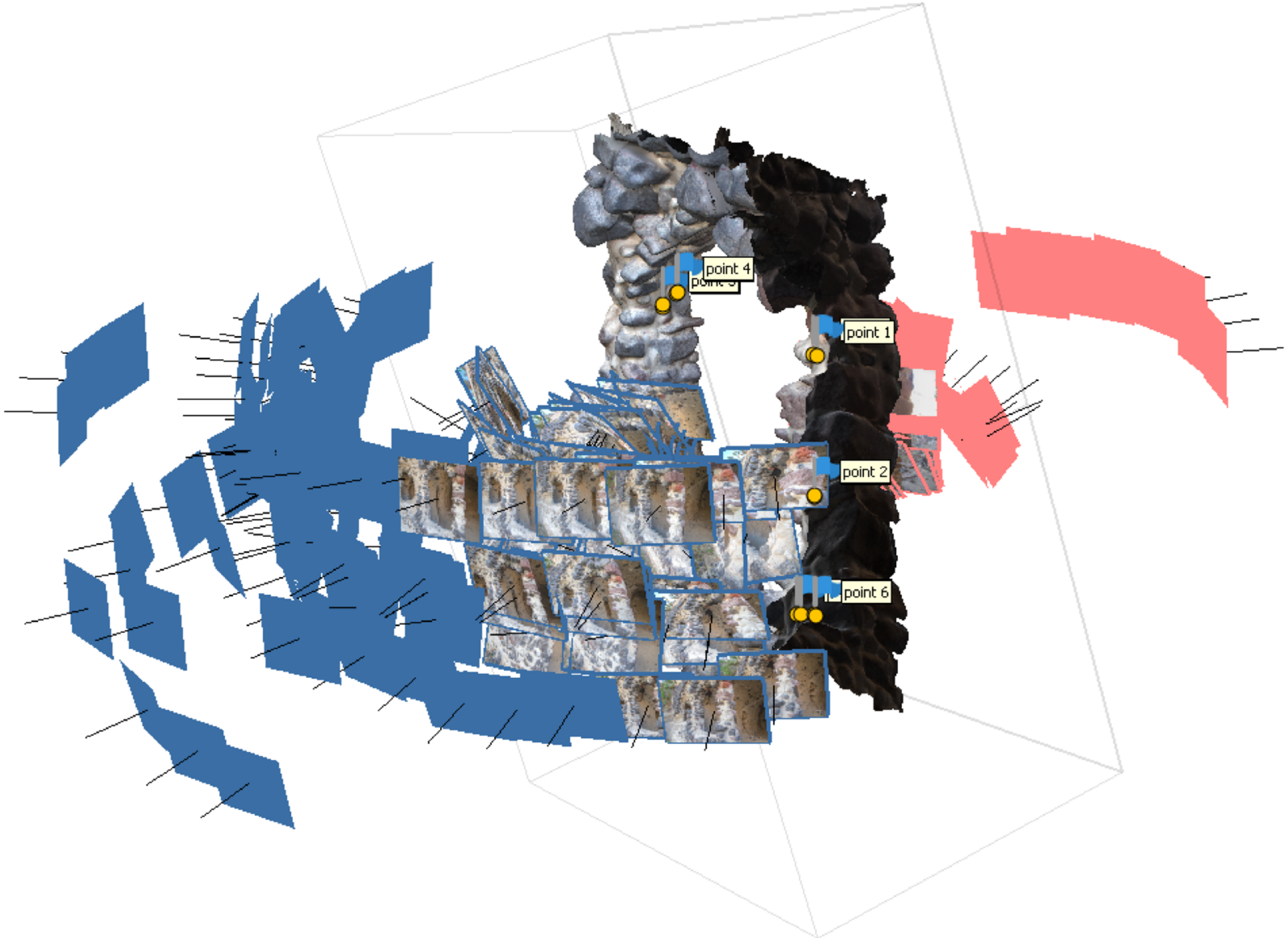


Figure 144. Screenshot from Agisoft Metashape, showing the inside and outside chunks of images that, when combined, create the complete 3D mesh.

Tiling

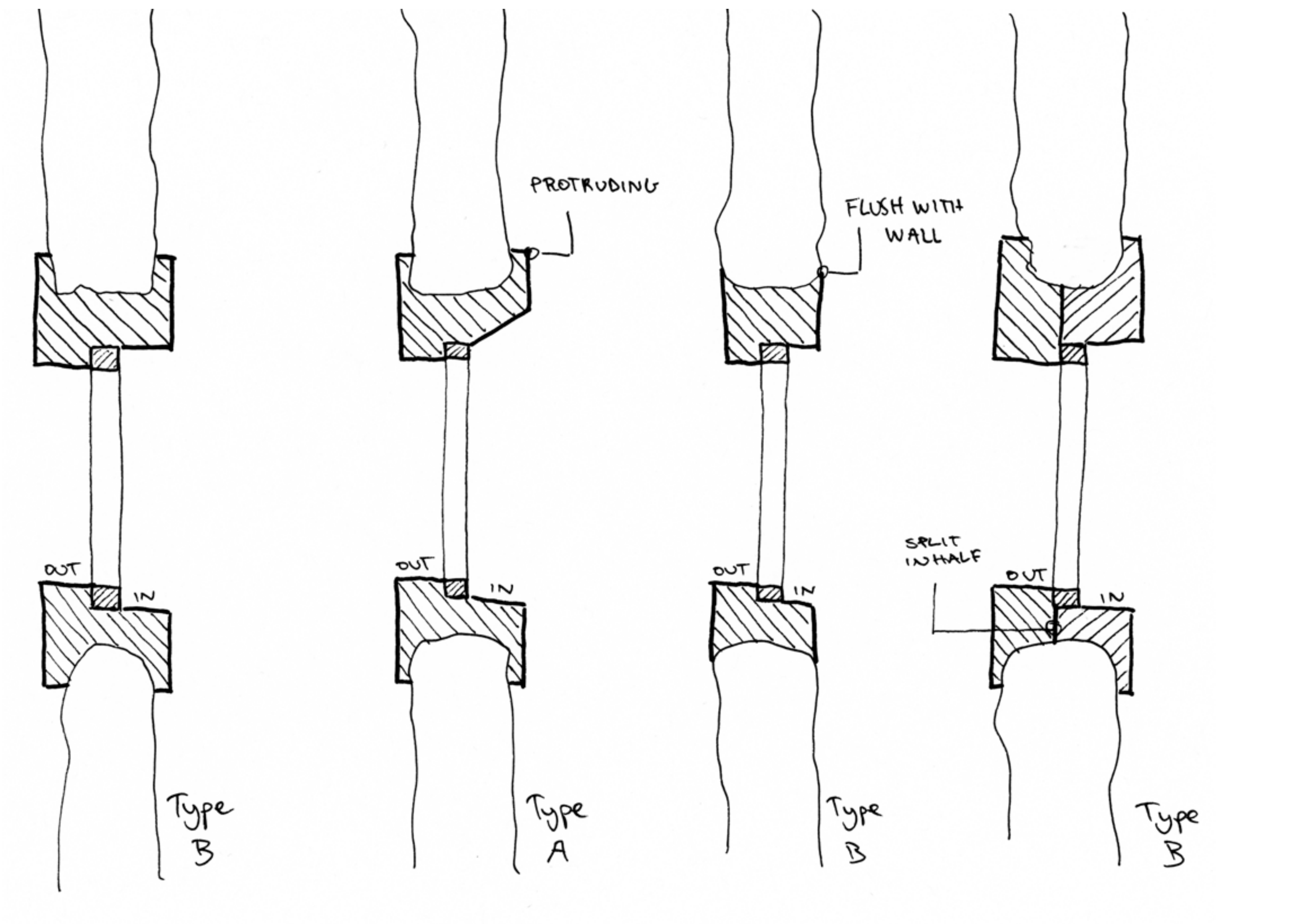
Following the conclusions of our site analysis, the architrave was split into a number of tiles for ease of printing, transport, and to allow craftsmen to remain involved in the installation process, helping to also train them in the use of digital tools.

Dividing the design
into tiles or bricks

However, the tiling of the design has more than just logistic advantages. Splitting the tiles according to the anatomy of a Theran architrave maintains continuity with vernacular architecture and makes each tile easier to print and assemble. Furthermore, it also facilitates the integration of non-printed support elements, i.e., the wooden window frame and lintel.

For this reason, the tiles were first split into four main sections before subdividing each of these: the sill, the lintel, and the left and right casings. Still, the exact location of the split had to be considered, since - as we saw earlier when analyzing Theran architraves - the window frame is visible from the inside, but not from the outside. This means that either the lintel and sill, or the side casings would have to feature a small step in their design. Depending on the printing direction of the tiles, this step would either be printable or not.

Figure 145. Effect of infill printing bottom caps in an LDM 3D-printed object.



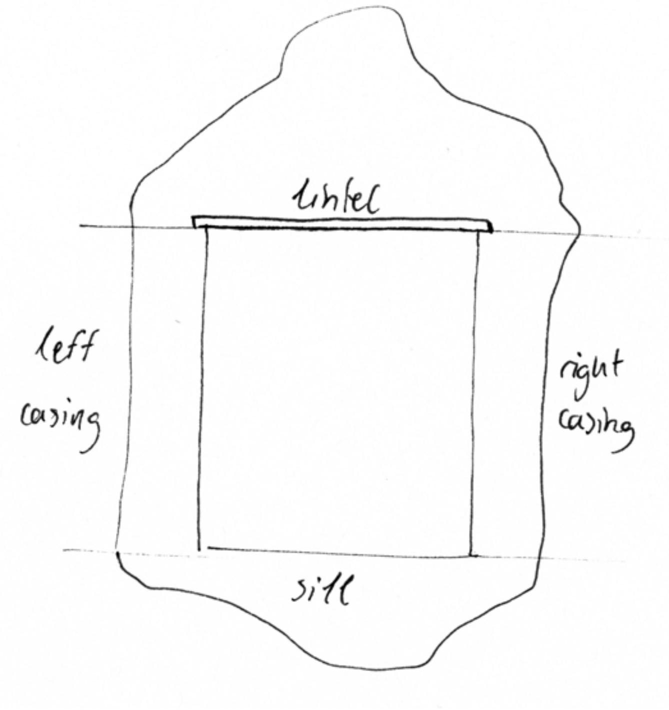


Figure 147. Initial splitting of the tiles according to the anatomy of a Theran window architrave.

Figure 146. Splitting of the tiles based on the integration of the frame, the transition between them and the facade, and the type of window used.

Combining craft:
digital and artisanal

Blending in
while standing out

Multiple options and ways of integrating the frame into the architrave were considered before arriving at the final design. In order to assess the feasibility of each option, the architrave was sketched in 2D from various angles and cross sections in an attempt to visualize how the tiles would fit together and how they should be divided to achieve both our desired aesthetic effect and their printability.

The printing direction of each larger element - the lintel, sill, and side casings - largely determined the exact division of the tiles. For starters, the way LSAM produces pieces was considered. When printing with parallel layers, a layering effect will be created in the direction of printing - i.e., in the vertical surface that wraps around the printed object. The caps - either on the top or bottom of the objects - will have a very different look and effect due to the layer deposition process. The top and bottom caps often look dirty and irregular - and not in a good way - and, for this reason, they would have to be hidden. In order to achieve formal continuity with the intervention, the printing direction of the tiles could therefore not be perpendicular to the wall itself, as then we would see the top of the tiles from the outside, and the bottom from the inside - or viceversa.

To make things simple and more aesthetically coherent, each element of the architrave would share a printing direction. At this point, having ruled out one of the three main printing directions, the choice between the remaining two was as much a stylistic one as it was functional.

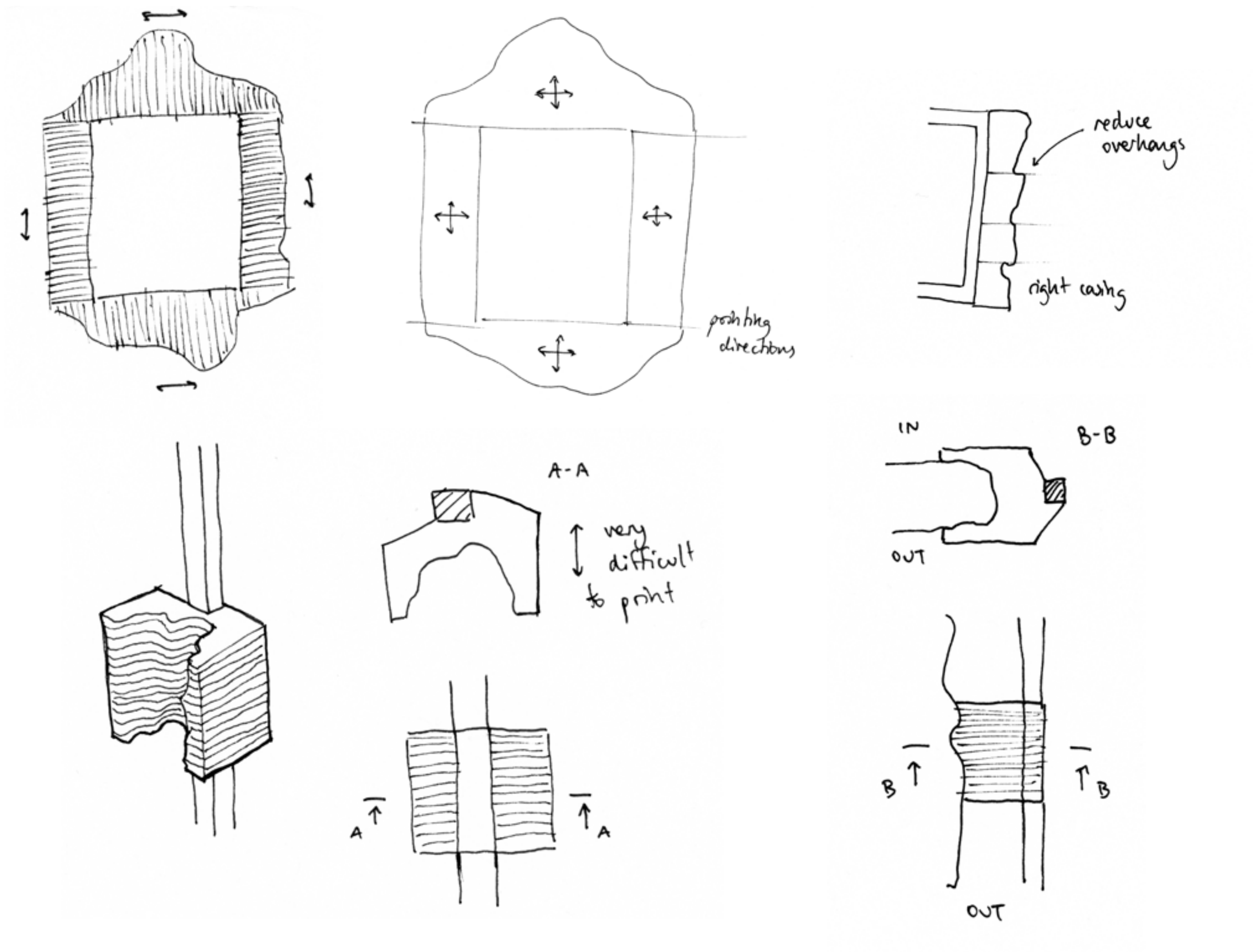
The easiest way to visualize this choice is by looking at the side casings. These could either be printed in either direction within the wall plane. Printing in the direction perpendicular to the frame would require printing on a non-flat surface, as well as multiple start-stop operations during the printing process. In the case of the lintel and sill, the same was true, making the printing directions of these elements perpendicular to each other. This would also create a clear distinction between each element, referencing traditional Theran architecture. The subsequent splitting of the tiles was done trying to eliminate large overhangs to facilitate printing. Theoretically, they could be divided in as many sub-tiles as necessary, but for this proof of concept, only 5 divisions were made per element.

Finally, the way the tiles wrapped around the wall gap was the result of the intersection between a type B window (since a type A window could not fit in this particular gap) and the scanned wall. Type A windows feature a domed interior, which would make printing slightly more challenging. Since both windows are used interchangeably in Agrilia depending on the dimensions of the house, designing the intervention based on a type B window made more sense.

The intersection between the architrave and the wall naturally created an irregular layering effect similar to that created by the falling plaster observed in the *Materiality* section, with the intervention fitting in as if it were filling a gap in the wall. All in all, the overall shape of the architrave, as well as the splitting of the tiles was largely influenced by the limitations imposed by the environment and the technology. In continuity with the original vernacular architecture of Agrilia, the context largely dictated the form.

Let the context dictate the form

Figure 148. Ideation sketches used to determine the printing directions of the tiles.



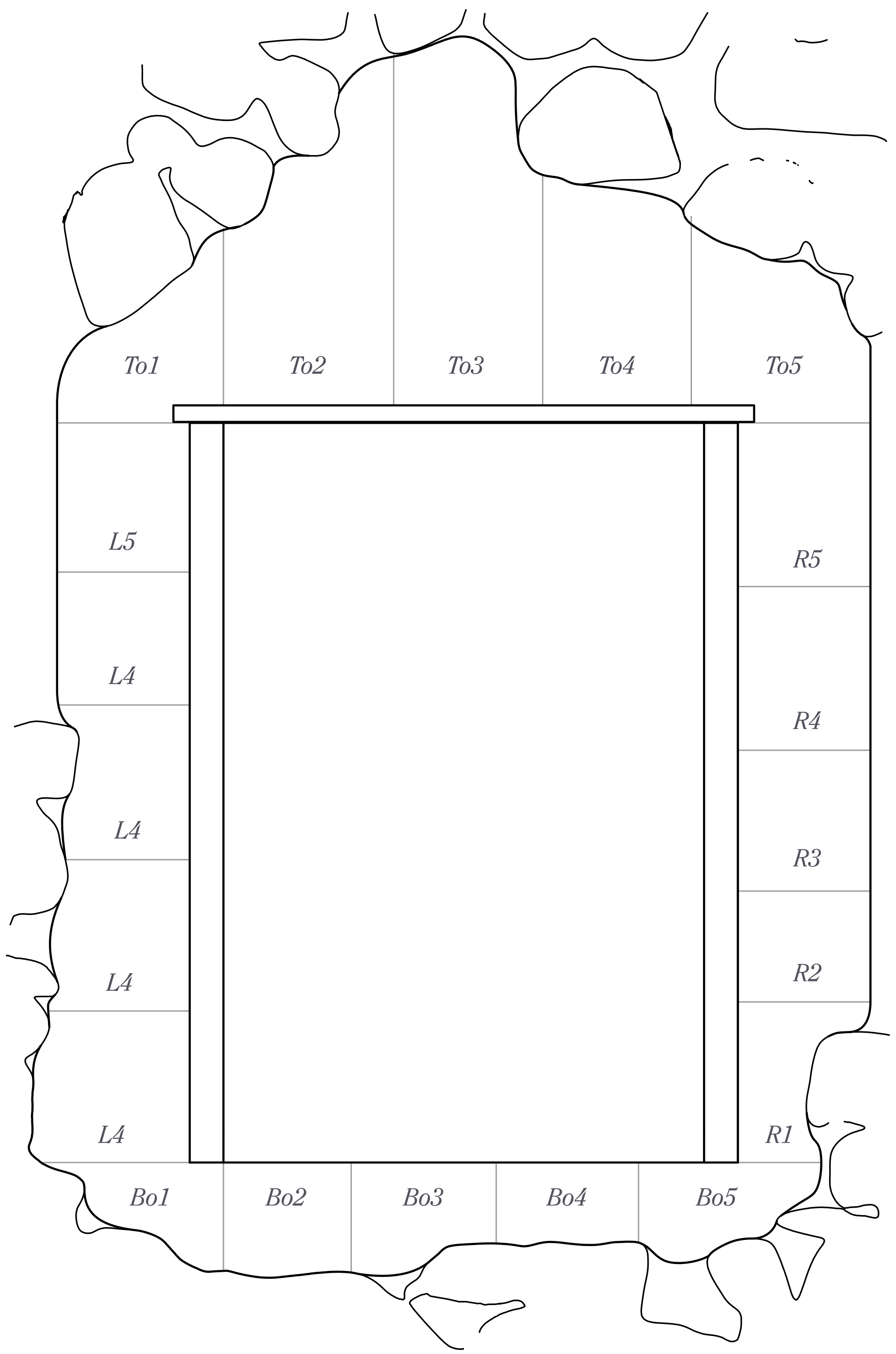


Figure 149. Architrave wrapping around the rocks that surroung the gap and showing the outside tile division.

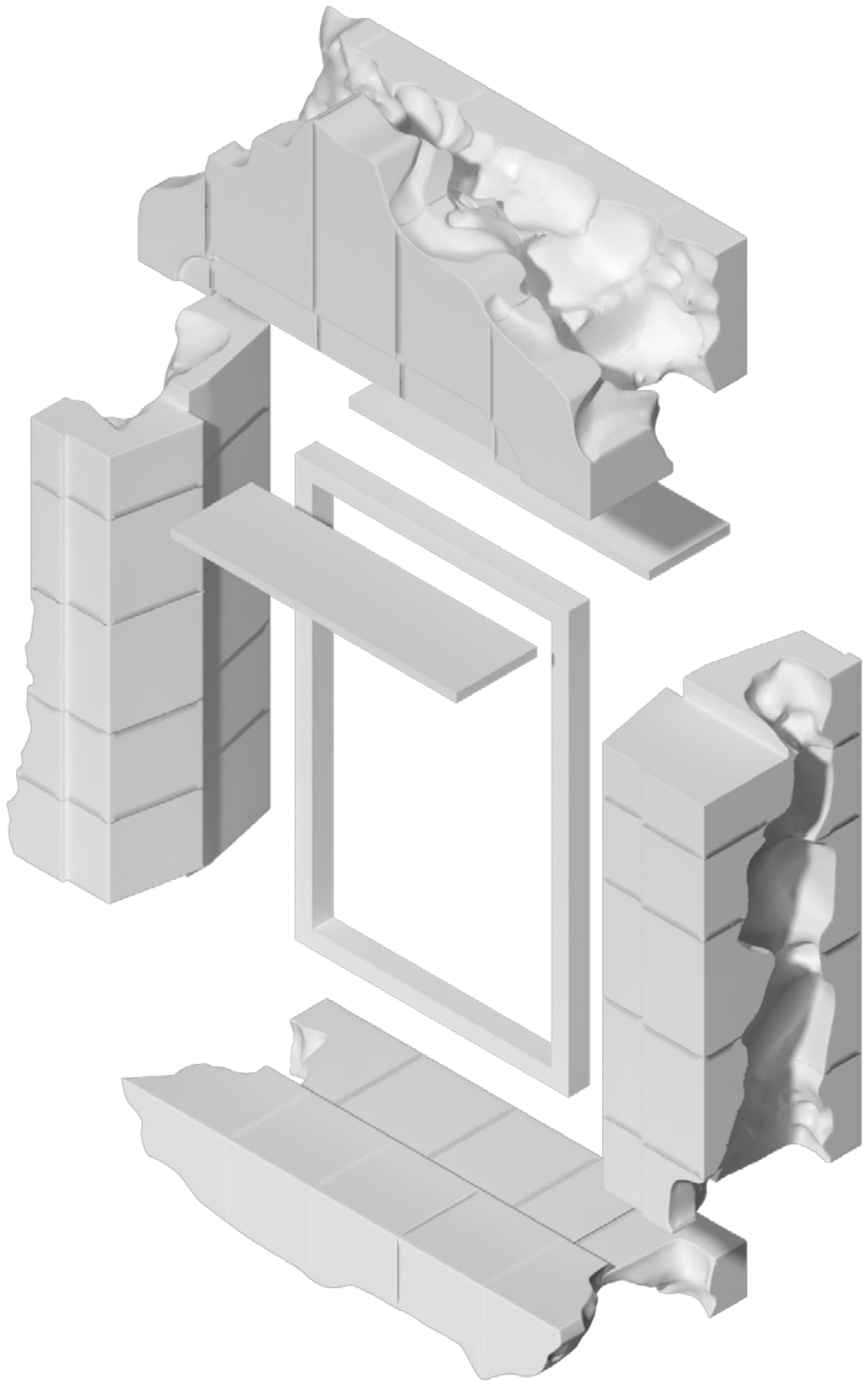


Figure 150. Exploded view of the architrave's tiles and integrated elements.

Integrated elements

The integration of wooden elements largely influenced the splitting of the tiles. At the same time, the printing directions chosen facilitated the integration of decorative details on the surface of the tiles.

Integrated window frame and lintel

The window frame, as well as the auxiliary wooden lintel used to distribute the weight of the printed lintel across the side casings marked two important divisions. First, the printed lintel and sill were split into an inside and an outside section, in order to facilitate the mounting of the frame and the printing of the individual tiles. Second, the tiles on the far ends of the lintel had their divisions marked by the position of the auxiliary wooden lintel.

Integrating elements:
support and design

Figure 152. Splitting of the lintel into inside and outside tiles for an easier integration of the non-printed elements (side view).

Figure 151. Detail of integrated lintel next to an actual integrated lintel in Agrilia.

Integrated decorative details

The decorative details featured in the design of the architrave were based on those of house no.19, at the entrance of the village. We saw earlier that most houses in Agrilia are not adorned with any superficial decorations. However, there are a few instances of decorative details present particularly around windows and doors. In this case, the detail creates an additional frame around the window by way of a 10mm indent in the plaster. This is a simple task for a 3D printer to achieve.

The copying of ornamental features, however, raises some questions as to the authenticity and aesthetic continuity of the intervention. In the case of a very complex ornament, 3D printing would likely be able to recreate it in high detail; however, the more complex the ornament, the more skilled the craftsman. In a site where craft is an essential form of heritage, its substitution by a modern technology such as 3D printing would not be respectfully informed. We have already established that some craft must be preserved in Agrilia, and that the intervention should facilitate this preservation of craft by combining it with modern technologies.

For this reason, Boulouki's work was consulted as to the importance of plaster ornaments as heritage in Agrilia. In their research project titled *Under the landscape*, Boulouki identified the most representative forms of craft in Thirasia. Among these, there was no mention of plaster ornament craftsmen or stonemasons, given the economic precariousness of the island. After all, one of the most characteristic aspects of Theran architecture is the lack of processing of the materials used - especially the stones. We can therefore conclude that these ornaments were minimalistic because they did not constitute a form of high craft, and their recreation with 3D printing does not supplant any form of traditional craft that needs to be preserved in the case of Agrilia.

Figure 153. Decorative detail in printed tiles vs decorative detail in house no.19 in Agrilia

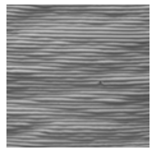
Continuity and recognizability

In the Adaptive Reuse case studies, it was observed that all of the examples that were analyzed achieved *recognizability, layering*, and the *perpetuation of heritage*, with one case study – that of the Kolumba museum, by Peter Zumthor – having a special focus on *continuity*. This example served as direct inspiration for the aesthetic part of the intervention.

The importance of materiality in Theran houses has already been established. Proposing to use Theran mortar as a printing material is a first step towards guaranteeing continuity with the ruins. However, despite the materiality of 3D-printed pieces relying heavily on material choice, there is a particular look and feel that FDM and LDM create which may impact how the architrave fits with the façade of the house. At the same time, however, Adaptive Reuse approaches analyzed in the case studies also emphasized the recognizability of the interventions following the suggestions of the Charter of Venice (ICOMOS, 1964).

One could argue that the continuity of this intervention is inherent in the material, while its recognizability is inherent in the use of 3D printing for its production. However, the materiality of a 3D-printed, layered object still had to be assessed. This was done through a laboratory experiment.

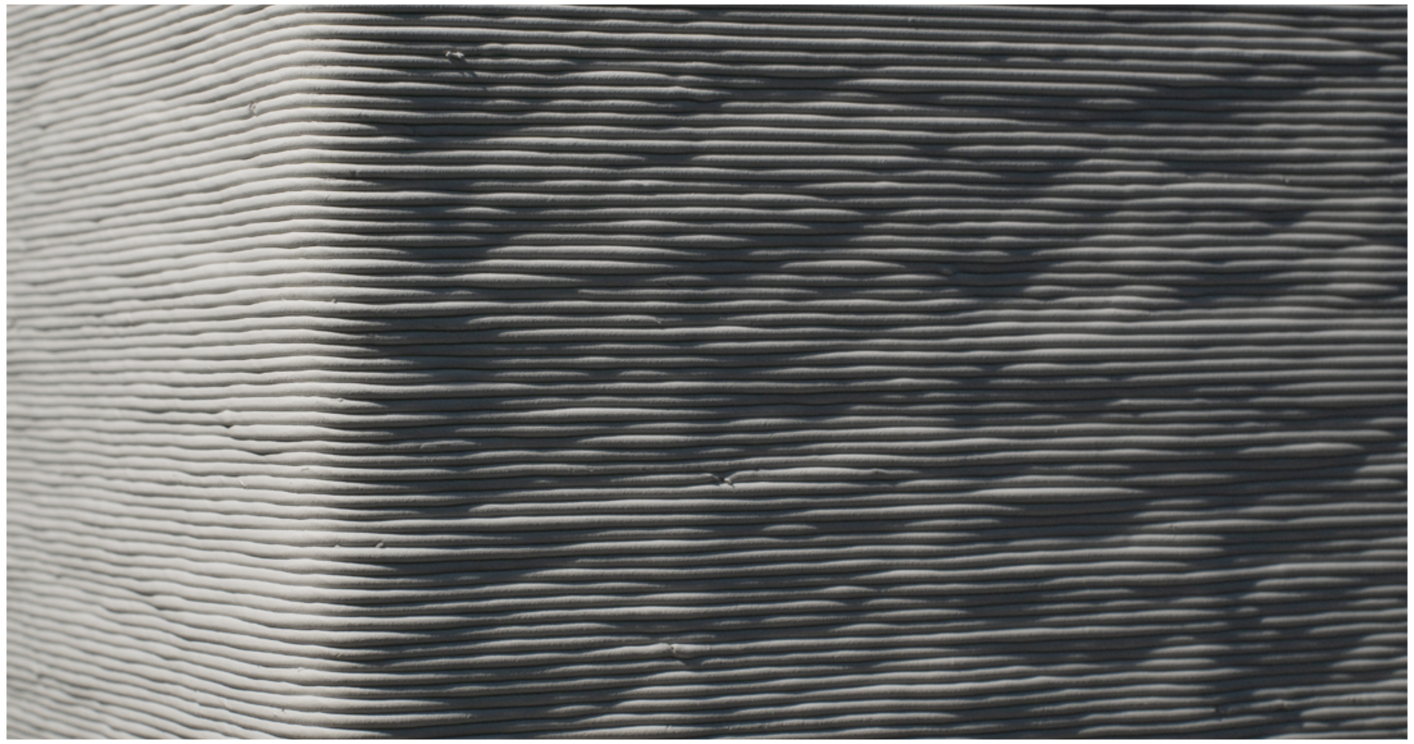
> *"Replacements of missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original so that restoration does not falsify the artistic or historic evidence" (ICOMOS, 1964).*



Artistic expression
through 3DP principles

Blending in
while standing out

Figure 154. Layering effect achieved in the final prototype, simulating a roughness inspired by the materiality of houses in Agrilia.



Printing experiment

3D-printed objects have an undoubtedly unique look to them. When analyzing the LSAM case studies in *Part II*, we saw this look influenced by the printing material, as well as changes in the dimensions and geometry of the layers. While printing with Theran mortar provides a certain continuity, the materiality of the pieces will also be affected by the microscopic qualities of the layer-on-layer deposition process. Therefore, in order to influence their materiality, we must influence the deposition process.

When discussing the cultural significance of houses in Santorini, Ionas Sklavounos – a founding member of Boulouki specializing in traditional building techniques – emphasized the human error inherent in vernacular architecture. Houses in Agrilia are a testament to this – their fluid organic forms and irregularly-shaped interiors are a result of the craftsmen's "handwriting". 3D-printed objects, in contrast, are precisely machined. The following experiments were conducted in an attempt to minimize this artificial, machined look by manipulating the layer-on-layer deposition process at a microscopic level, aiming to achieve macroscopic changes in the object's perception.

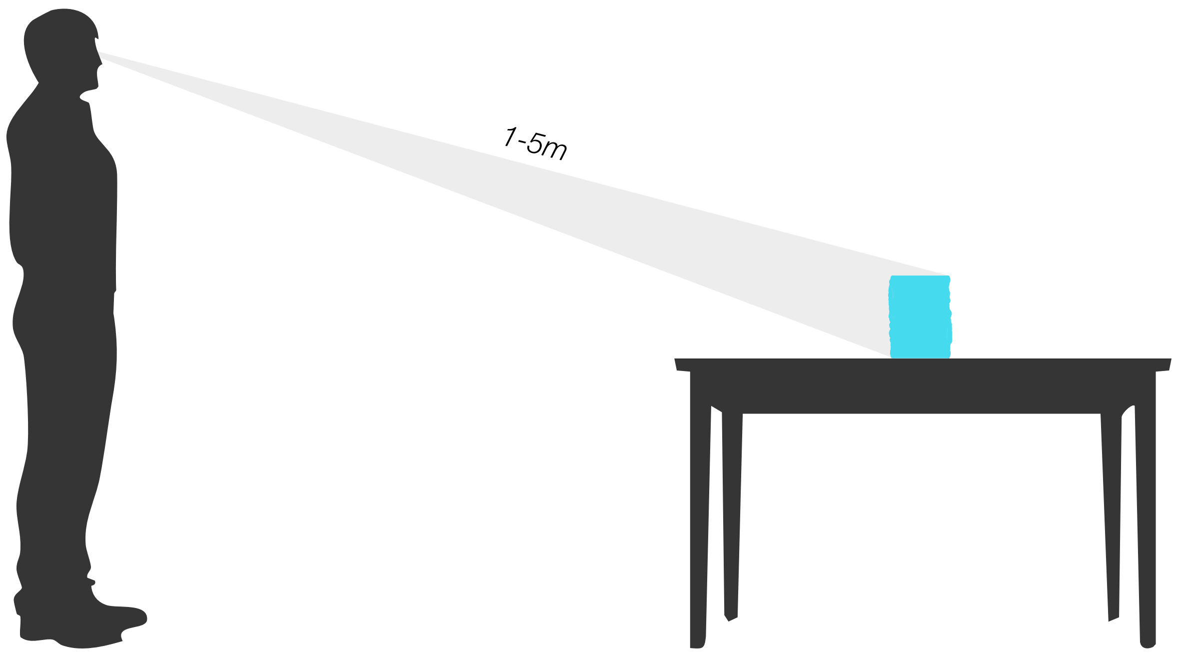
Methodology

Our own handwriting was introduced into the prints by crearting a form of superficial "noise" on the surface of the tiles. This was achieved by offsetting points along a tile's toolpath according to a black and white bitmap image. The points were offset perpendicular to the toolpath, resulting in a rough surface texture.

Considering layer height (LH) and texture offset as the two printing parameters affecting the surface look of a tile, 12 test blocks of 20x10x20cm were printed with all the parameter combinations. Layer heights of 2, 3, and 5 millimeters were used, as well as texture offsets of 0, 1, 2, and 3 millimeters. These numbers were based on previous printing experiments with varying nozzle sizes and printing parameters. These initial experiments were done in order to narrow down the parameter combinations to include in the official experiment.

To assess the macroscopic effect of the variations in the toolpath, each tile was judged from distances of between 1 and 5 meters.

Figure 155. Experiment setup.



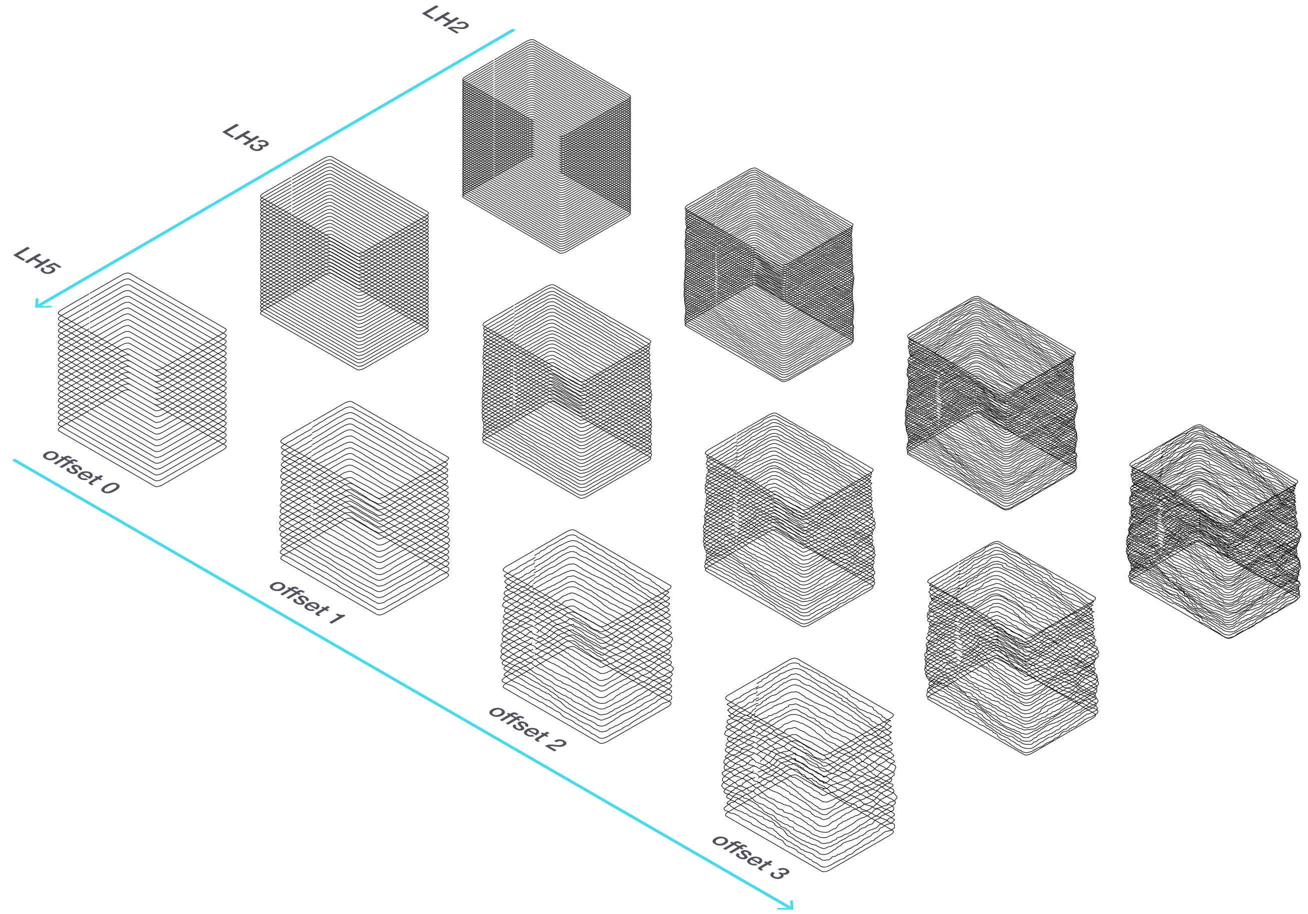


Figure 156. Printing toolpaths for test blocks with varying layer heights and pattern offsets.

Results and discussion

Higher layers result in shorter printing times, and smaller pattern offsets do too (although very slightly). However, toolpath variations in taller layers severely warp the surface of the tile; so much so, that it could cause problems during their assembly. The tiles printed with a LH of 5mm were instantly ruled out because of this.

Additionally, when printing different layer heights with the same nozzle, there seems to be a certain threshold after which the machine is not able to extrude enough material to guarantee proper binding between consecutive layers. As the printer follows the toolpath, it pushes down on previous layers, compacting the material and eliminating imperfections in the layers. In the experiment, LH5 tests featured imperfections even without introducing a pattern offset. Further variations in the toolpath, at this point, produced highly unpredictable results.

Finally, while a layer height of 2mm allowed for greater offsets without compromising the overall geometry of the piece, the ideal offset was found to be between 1 and 2mm. Accounting for the irregularities in the material as well, this amount of texture should be enough to give the piece a rough feel without compromising its integrity or making its printing and assembly too unpredictable.

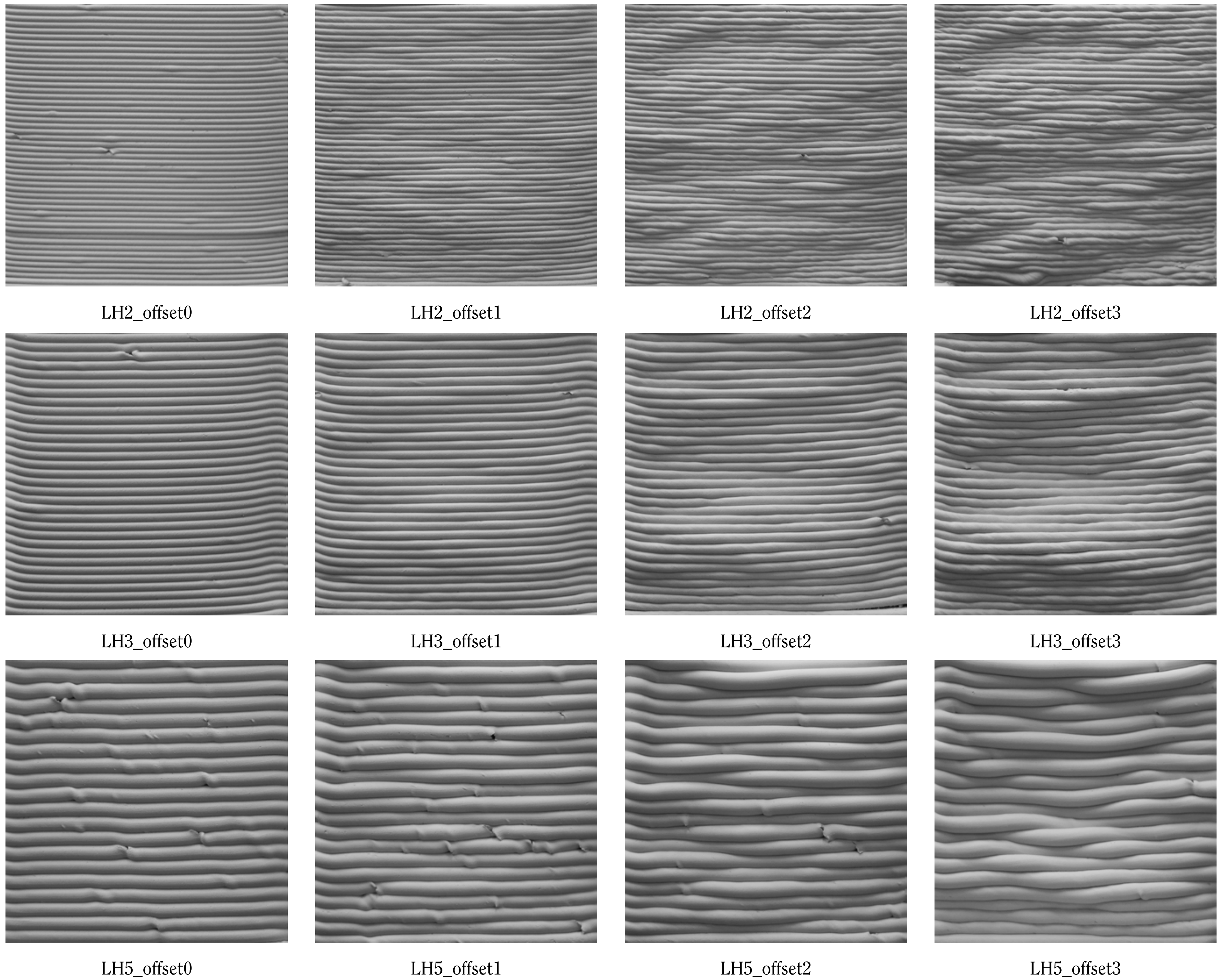


Figure 158. Printing experiment results.

Combining craft:
digital and artisanal

Gradient material properties

Earlier in the project, in the *LSAM Case Studies,* IaaC's *Architecture Continuity: From Materiality to Environment* stood out because of its integration of support elements, but also its use of gradient material properties. In this project, students used variable infill densities to shift the center of mass of a printed archway, allowing for unreinforced printing. In Agrilia, craftsmen were traditionally able to build unreinforced domes thanks the properties of Theran mortar and the lightness of pumice stone.

Theran mortar's binding strength meant that it could hold its own weight when hanging from the ceiling of a cave; when used with pumice aggregates, it became light enough to allow for the construction of domes up to 4m in diameter (FIlippidis, 1983).

When it comes to openings in the building envelope, we see the same properties of Theran earth and pumice stone being exploited. Windows in Agrilia feature a density gradient. The as the height of the wall increases, so does the pumice stone content of the mortar, with lintels often being composed exclusively of this stone. Replacing these lintels would require achieving the same vertical density gradient in the 3D-printed pieces across the entire architrave.

Figure 159. Pumice stone lintel in an interior partitioning wall. In this case, an auxiliary wooden lintel distributes the weight of the stones across the side walls. However, we can observe in its decay that the pumice stone, with the help of mortar, is hanging above the shelf and supporting all of its own weight without weighing on the wood.

In the tiles, the infill gradient is achieved by creating a double-walled surface and filling in the space between the two walls with a triangular infill pattern. As the height of the tiles relative to the ground increases, the space between the two walls becomes narrower and the infill pattern, less dense.

Naturally, there are many types of infill a 3D-printed tile can feature. This, however, was the easiest pattern to apply to a wide variety of tiles through a parametric code generated in Grasshopper. The interor wall of the tile is created by negatively offsetting the outside surface, an operation that can be done on every one of the tiles without needing to adapt the prametric code each time. Furthermore, it creates two distinct parameters that can be used to control the density and weight of the tile: the distance between the inner and outer walls, and the amount of segments in the triangular pattern.

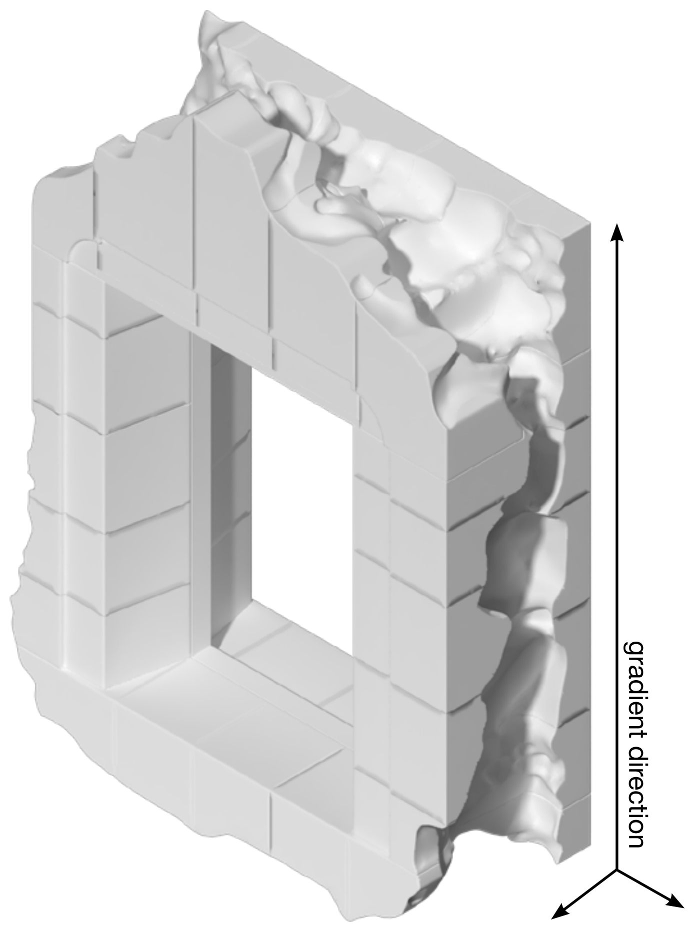


Figure 160. Isometric drawing showing the direction of the infill gradient.

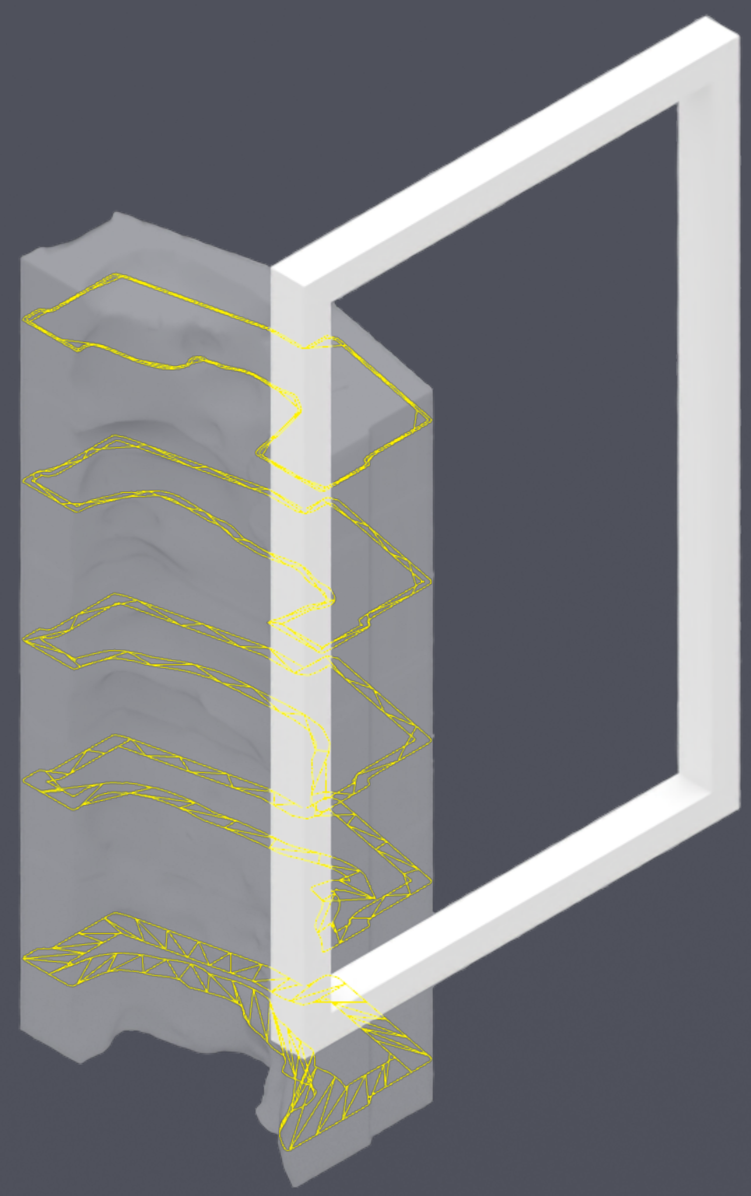


Figure 161. Isometric drawing of the left casing tiles, showing the infill decreasing with the height of the tiles.

Material experiments with Theran earth and lime

The use of local materials as an opportunity for added value creation was identified during the *LSAM Case Studies* and reiterated throughout the analysis. It was one of the criteria based on which Agrilia was chosen as a site and it ended up constituting the site's most unique form of tangible heritage.

Although we cannot say for certain whether Theran mortar can be printed, this section features some initial observations that point toward a promising future for the intervention. Seeing as a thorough assessment of the printability of Theran mortar is outside the scope of this project, the experiments carried out here focused on the material's extrudability and stackability. Based on Aditya Parulekar's (2020) research on stucco ornament printing, the material's behavior and suitability for 3D printing is evaluated based on: pumpability, extrudability, buildability (or stackability), and aesthetic compatibility.

In the context of this project, the material's pumpability could not be tested due to the lack of a concrete pump at LAMA's facilities. Additionally, its aesthetic compatibility was considered a given, since the material tested was sourced from the site and should look identical to that which was used in the houses. Instead, it was compared to the clay used for the 3DP experiments. Therefore, the experiments centered around the material's extrudability and buildability.

The Theran earth used was sourced from the mines in the south coast of the island and processed at the *Laboratory of material science and resitance* of the *National Technical University of Athens.*The lime with which it was mixed to acquire its binding properties was CL90-quality air lime with less than 3% Mg content, as per Boulouki's specifications in their own material testing (Boulouki, 2022).

The mix tested featured a **1:6 lime to Theran earth ratio** with varying amounts of water. This ratio was chosen based on Boulouki's experiments. In their research, they tested 7 samples with different concentrations of Theran earth and lime to assess their compressive strength and shrinkage. M1:6 showed the second greatest resistance to compressive forces, at 2.27MPa, and the lowest shrinkage coefficient, at -0,35% (Boulouki, 2022).

Printing with
local materials

Figure 162. Theran earth mines on the south coast of Thirasia.

Figure 163. Sifting of Theran earth through a 1mm sieve.

Figure 164. Theran earth sourced from the mines in Thirasia.

Figure 165. Setup image showing all the tools used for the test.

Setup and mixing

The setup used for the experiment included a scale, two separate bowls for measuring the Theran earth and lime, a hand mixer, two beakers for adding water, a spatula, rubber gloves (due to air lime being highly alkaline), a variety of syringes, and a caulk gun.

Theran mortar behaves very similarly to cement-based mortars. Its mixing process is therefore also similar to that of 3D-printable mortar or concrete mixes. First, the Theran earth and lime were mixed before adding any water. Then, water was added in small increments so as to avoid clumps forming in the mix. The mix has to be agitated continuously and thoroughly; first, to ensure homogeneity in the material (since we could not trust the results of a test carried out with a non-homogenous mix) and second, to keep it from hardening.

The clay that had been used until this point for printing experiments hardens in the absence of moisture. For this reason, WASP - the printer's manufacturer - uses a closed, compressed air system that feeds material into the extruder using pressure. Cementitious materials, on the other hand, harden through the crystallization of various compounds in the presence of moisture. This means that, to keep crystals from forming, the material must be agitated continuously. 3D printing systems that use cement-based mixes make use of a mixer-pump system that continuously mixes the material while it pumps it toward the extruder with the help of an archimedes screw. Now, not only does this make the WASP 4010 LDM printer unsuitable for printing this material, but attempting to print with it using a compressed air system would cause serious blockage in the machine, potentially leading to a pressure buildup that could make the material tank burst. For this reason, the mix was only tested using hand-operated syringes and an electric caulk gun.

Before assessing the material's extrudability and buildability, the correct consistency had to be reached. In Boulouki's laboratory research, test cylinders were cast using a mix with 30% water content relative to the combined weight of Theran earth and lime. For this experiment, 20% of water was added before adding more in 10% increments. As the material was being mixed, two tests were performed to assess its readiness for printing: first, spreading it on a flat surface before continuing to mix, to make sure it did not feature any granulometric inconsistencies that could clog the nozzle during the experiment; and second, holding it vertically with a spatula above the bucket to see if it could hold its own weight. This second test is widely used in 3D concrete printing.

Having reached our desired consistency, we could proceed with the experiments.

Figure 167. (Top) Material mixing.

Figure 166. (Left) Material spread on a flat surface to observe granulometric inconsistencies.

Figure 168. (Right) Spatula test to assess printing consistency.

Extrudability

The extrudability of the material mix was tested first using the manual syringes, before moving on to the electric caulk gun.

The first insight gained from this test was that the material was almost impossible to push through the syringe using compression. The first few attempts did not yield any results; even upon increasing the water content to 50% and cutting a larger nozzle hole, it was still not possible to push any material through using manual strength. Using this water content (50%), and moving on to the caulk gun, material could only be extruded within a few minutes of loading into the tube. After a few attempts, the entire tube was able to be pushed through the nozzle continuously. It is important to remark here again, that 3DCP systems do not use compression to push material through. In fact before, being able to extrude any material, the syringe would sometimes drip water, suggesting that the caulk gun was squeezing water out of the mortar instead of pushing it through the nozzle.

The few successful tests, however, showed promise. To be certain, experts were brought in to observe the testing from Vertico B.V., a company specializing in 3DCP. They asserted that the mix would certainly be printable, though its buildability would have to be assessed.

Buildability

The material's buildability (or stackability) refers to its ability to hold its own weight and pressure from upper layers when it is not yet cured. That is, if multiple layers can be stacked on top of each other without it collapsing.

Vertico uses a portland-cement-based mix that is injected with accelerant as it comes out of the printhead. What the accelerant does is enhance the exotermic reaction that leads to the crystallization of the mix, essentially making it harden faster, allowing it to better hold its own weight. What we did in this experiment is considered 1K (or one component) printing. 1k printing cannot produce very tall objects, but should still be stackable to a certain extent.

In this regard, Theran mortar proved exceptionally stackable. Probably due to its lightness, the effect of stacking multiple layers on top of each other in was barely observable. The experiment's results are not as realiable as those of a real printing test, as the "toolpath" is controlled by a human hand instead of a robot. Still, the material behaved exceptionally well under the circumstances. Stackability was tested in single-walled cylindrical shapes, deforming minimally under pressure from top layers.

Aesthetic compatibility

Lastly, the aesthetic similarities between the stoneware used for 3DP experiments at LAMA and Theran mortar mix M1:6 were assessed.

As we mentioned before, the ratio of Theran earth to lime was chosen based on the material's mechanical performance. However, upon drying, this mix proved to have a color strikingly similar to that of stoneware clay. A higher lime content would have made it whiter and a lower one, slightly more gray.

Naturally, the different chemical makeup of the two materials makes stoneware matte, while Theran mortar is slightly glossy due to the crystallization that happens as it cures. Finally, as we expected, Theran mortar is slightly rougher due to its granulometry.

Figure 169. Comparison between Theran mortar M1:6 and 3DP clay.

Figure 170. Extrudability test.

Figure 171. Stackability test.

Demonstrators

Two prototypes were made as a proof of concept that integrates all the aforementioned features into the design of the intervention. First, a 1:1 scale tile was printed in stoneware clay, showcasing the infill geometry chosen for the tiles, as well as the suggested materiality of the intervention, achieved through toolpath manipulation in the layer deposition process. Then, a 1:5 scale model of the entire architrave was printed in plastic, showing the integration of support and decorative elements into the design of the architrave. Finally, a small cylinder of extruded Theran mortar was included to showcase the look and feel of the real material when printed.

Figure 173. Small Theran mortar cylinder extruded during the material tests.

1:1 scale tile

This tile was printed following the recommendations of the printing experiment conducted in the Continuity and recognizability chapter. It was printed with a 6mm nozzle, a layer height of 2mm, layer width of 8mm, and a pattern offset of 1.5mm. Only one tile was printed at this scale due to its dimensions and the large amount of material required to print it. Tile Bo2 was chosen due to its simple geometry, which facilitated the slicing and printing process. The clay used in the laboratory also proved to be much more similar in color and texture to Theran mortar, which makes this demonstrator resemble the actual intervention even more closely.

1:5 scale model

This scale model was printed in PLA due to its versatility and fast printing time. Its primary aim is to show the integration of the window's support elements, as well as its decorative features, but also to serve as a storytelling tool in the project's presentation. A single 1:1 scale tile is difficult to interpret, place in 3D space, and imagine the rest of the design around it. A scale model such as this one facilitates an understanding of how the intervention works, how it adapts to the gap in the building envelope, and how it is put together. The window frame and lintels were printed in a different color to make them more visible.

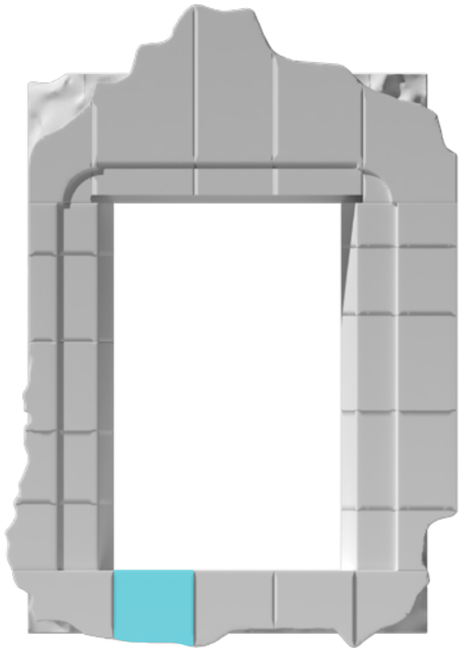


Figure 174. Tile division highlighting tile Bo2.

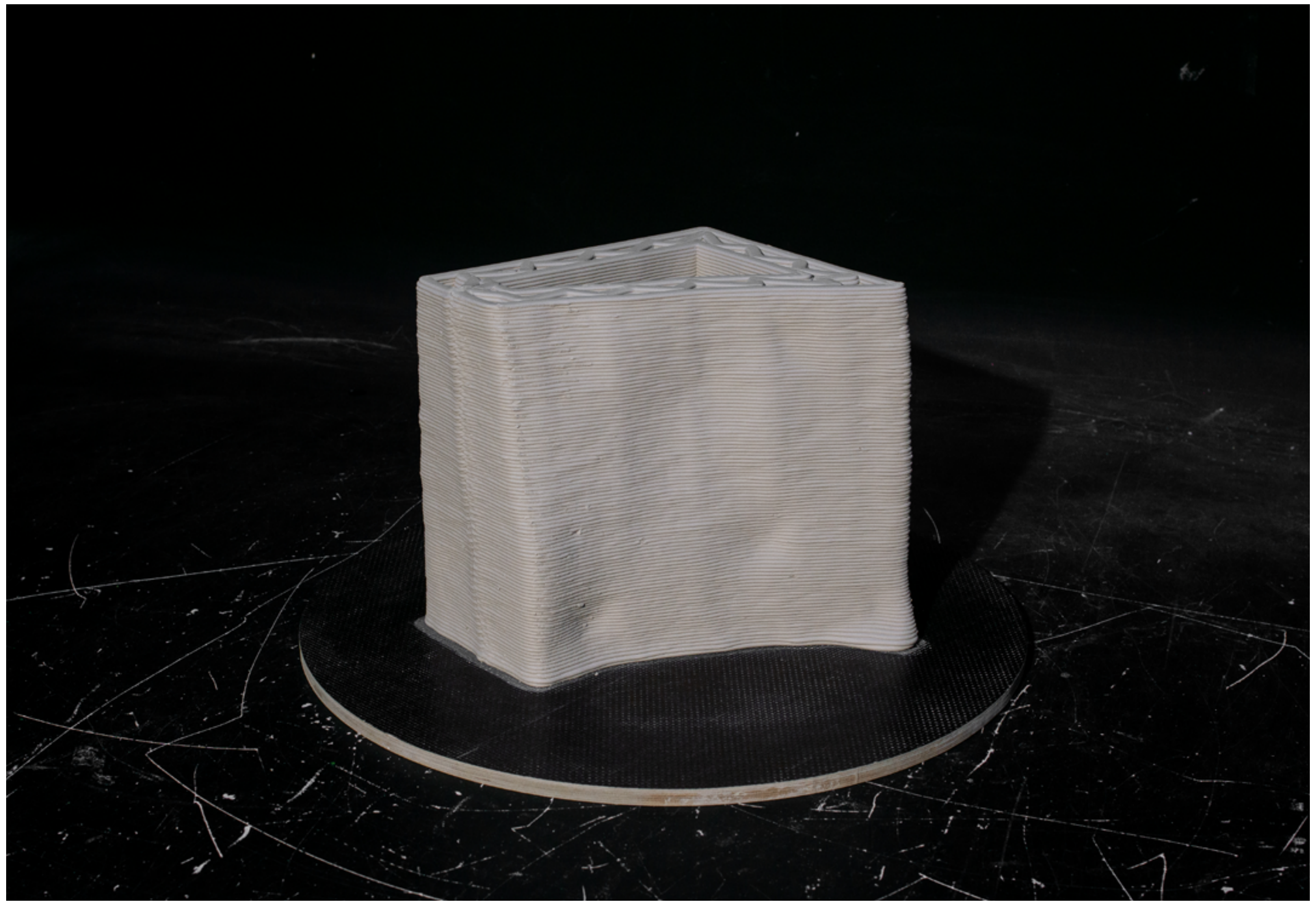


Figure 172. 1:1 scale tile printed in stoneware clay

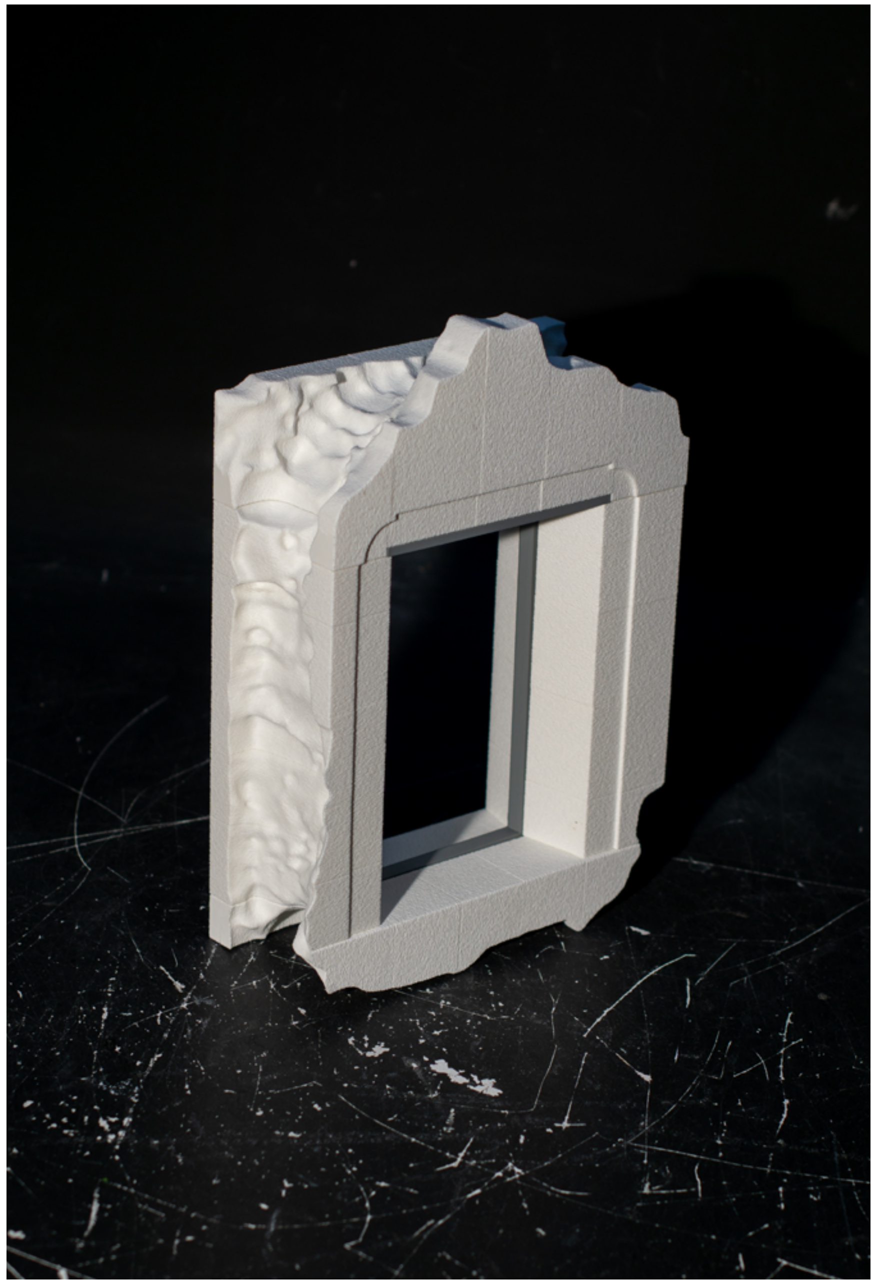


Figure 175. 1:5 scale model printed in white and gray PLA

Conclusions

This project began with an in-depth analysis of the disciplines of Adaptive Reuse and Large-Scale Additive Manufacturing through a series of case studies that were meant to identify opportunities for added value creation in preservation through LSAM. At the end of this first research phase, some opportunities were proposed in the form of a design tool. This tool would help find preservation projects where LSAM could be applied and serve as an aid in the intervention design process.

In order to answer the research question posed in the beginning of the research, this theory had to be applied to a real-world case study. It is therefore through the case of Agrilia and the revamping of its cave houses that the conclusions of this research are drawn and the main research question is answered.

Figure 176. Ancient Arkesini, in Amorgos - one of Santorini's neighboring islands. The site shows traces of use dating back to the Early Bronze Age, all throughout the Cycladic, Minoan, and Hellenistic periods, and through to the Roman Empire, Byzantium, and modern Greece. On top of the hill currently sits a church from the 19th century, built on a foundation of Roman concrete from 500AD.

Figure 177. Rendered architrave

LSAM and Adaptive Reuse

We mentioned in the very beginning of the project that there are practical, almost self-evident reasons for which Large-Scale AM should be applied in preservation. Heritage is already being preserved digitally and AM naturally fits in this gap in the preservation workflow.

However, if we perceive preservation in its most rigid sense - that of restoration or maintenance -, there is hardly any room for LSAM to show its true value as a building technology. Adaptive Reuse, on the other hand, presents an opportunity for design to be introduced into the process. The adaptation of a building for modern use brings forth new requierements, one of which is enabling the past to dialogue with the present through the design of an architectural intervention. And yes, Adaptive Reuse very often centers around the new use of the building and this, in turn, is what receives most of the protagonism. One could argue that a revamped building that serves a modern version of its original use cannot be considered Adaptive Reuse, but a modern house is hardly the same as a vernacular one, and their users' needs vary more than one would think.

The important thing about Adaptive Reuse is that it enables creative freedom, allowing projects to add a layer of cultural significance to the site with their intervention. After all, what we are trying to preserve was new at some point, and our intervention will one day be old and perhaps deemed valuable enough to preserve. This creative freedom shines through in the AR case studies; five different sites with wildly varying uses, requirements, and cultural meanings. The outcome of these projects is unique to their designers' vision. Though constrained by the significance of the ruins they encountered, they each had their own artistic approach, their own interpretation of what was important - what should be highlighted and how. In fact, in most cases, the heritage sites have served multiple uses over their lifetime, showing traces of many historical periods, each stacked on top of the other, contributing to the stratigraphy of interventions across history and adding to the cultural significance of the site.

Interventions are supposed to be a reflection of the present time. If we take for granted that, at some point, they will be buried under a number of succeeding layers, they will have to represent the time period from whence they were introduced into the site. Now, Adaptive Reuse therefore allowes us to use 3DP as a technology, and its use is further justified by its relevance in the present time. However, for the intervention to achieve true value, the technology itself must show its own.

By playing to LSAM's strengths and AR's requirements, we can design an intervention that achieves all of the above. In the end, preservation as a discipline is so vast and its intepretations so varied that, though a site may call out for its damage to be fixed, it very rarely specifies how. It is up to us to figure out how to work with the site and everything it has to offer to find out where we can introduce our own handwriting; what elements of it we can and should reuse, and what we should leave intact; what we can learn from its previous users and what we can improve upon; and, finally, what the implications of its repair are for its broader sociocultural context.

Agrilia as a case study

Going back to our design tool, which we first used to identify opportunities for LSAM in Agrilia, we can now materialize some of the proposed connections from the first part of the research.

In this project, LSAM was explored in its potential to create value through a set of features that are unique to it as a manufacturing technology. Mapping these to a real-world site requires some ingenuity. The way these features were used in the case studies may not be exactly the same as they were interpreted in the case of Agrilia. Nevertheless, the principles remain the same, and the specificity of 3D printing as a technology does too.

Three of the features, in the end, constituted a translation of Theran building techniques into the present: integrated support elements, gradient material properties, and integrated design elements. This may not add value in a way that is new to the site, as the original techniques already achieved the same purpose, but they provide continuity to the site's interventions by learning from its original designers. Inspiration in a project like this does not come only from form and materiality, but from anything that grants cultural signifcance to the site. After all, what better place to look for inspiration than in the knowledge of the site's previous users?

The rest of the features - namely new aesthetics, repair, and km0 material -, were a result of the site's requierements and opportunities. Repair came from the type of damage present in Agrilia: gaps in the building envelope. Among the recurring architectural features observed, they all featured the same type of damage, which can be reduced to "missing pieces". This is the result of how the material used for their construction behaves in the presence of decay. The dust, wind, and rain slowly chip away at the facades of the houses, causing the mortar to degrade and the stones to fall. Repairing Agrilia therefore implies fixing these gaps, and using 3D scans to do so is almost unquestionable in the context of LSAM and AR.

Km0 material is the result of an opportunity provided by the site, harnessed by 3D printing. Although it is self-explanatory, its value must not be underestimated. The use of a local material not only guarantees continuity with the site's original formal qualities, but it continues a sustainable building tradition that has been lost throughout history. Sourcing and processing of materials on site often becomes the pretense for an entire architectural project. Tecla, one of the LSAM case studies is entirely based on this.

Finally, the new aesthetics feature is inherent in LSAM, but its potential can be expressed in a variety of ways. The aim of this intervention was to find a middle ground

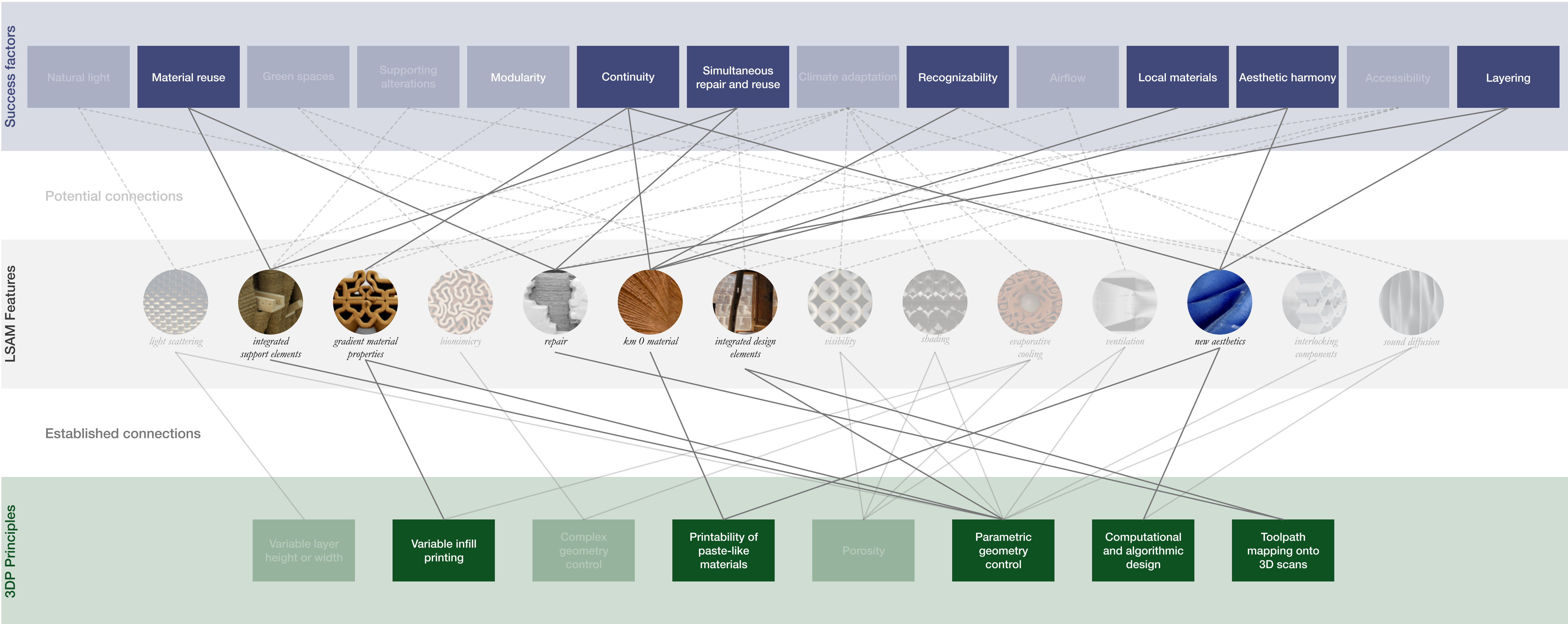


Figure 178. Opportunity mapping for LSAM in Agrilia.

between the layer-on-layer look of typical 3D-printed objects and the materiality of the site. Though 3DP can produce myriad geometric forms, its geometry is often constrained by its application (as it was in this case). However, the uniqueness of the layer deposition process that enables FDM and LDM printing also enables the generation of microscopic irregularities in each layer which, when added up, contribute to an overall change in the look and feel of the printed piece. As we mentioned before, at this point, aesthetics comes down to the creative approach and interpretation of the designer, and there are infinite ways in which the aesthetics of the pieces could have been affected.

Learning the language

Following this design process - the methodology outlined in the beginning of the project and the design tool that resulted from the theoretical part of the research -, provided a systematic approach to the intervention. This made every decision have a precedent that could be traced back to a specific point in either the background or the site analysis.

The analysis itself yielded a number of insights. While some of them were directly translated into the design, others were not. Still, the process made it clear that conducting such an in-depth analysis is absolutely imperative for any preservation project. The way the analysis is structured, we can see every architectural detail in Agrilia being the direct result of an environmental factor; either purely environmental - the morphology of the island or its geology -, or influenced by its broader cultural, social, and historical environment - the caves themselves as a form of dwelling are but the result of a social division present in Theran society since the middle ages.

Approaching the project in this way and becoming increasingly aware of this sequence of translations inadvertently made every aspect of the intervention a further translation of each of these values. After all, repair is but another stage in the site's history and is a direct result of the sequence of historical events that have led to the village's abandonment and consequent decay.

Using the design tool to brainstorm potential interventions during the visit enabled specific features of Theran architecture to pop out, such as its integration of support and design elements into the building fabric. The tool itself provided a very unique lens through which to look at the houses, almost introducing bias into the analysis. This is why it had to be carried out so thoroughly and why the site had to be visited twice. Warlamis (1995) remarks how vernacular architecture can only be truly experienced by living in it. It responds to our deepest, most primal evolutionary instincts, and this is something that literature cannot really express - it must be experienced first-hand. This holistic approach to the analysis coupled with the LSAM lens the design tool provided us with, enabled us to recognize the value inherent in Theran vernacular architecture.

Recognizing this value is somewhat subjective. Although there are scholars and academics that have identified specific aspects of Theran architecture as worth preserving, the case of Agrilia is unique even within the context of Theran architecture. It is therefore possible that this subjectivity may have led us to consider certain aspects of Agrilia as more important than others simply because they could be translated into the present through 3D printing. This is where literature, experts, and a self-reflective approach to the analysis come in. While we cannot say for certain what is truly important to preserve and how this should be done, it is all part of the process. Even such a thorough analysis can always yield results that do not match with the heritage of the site.

Each site has its own language - its own grammar and syntax, phonetics and etymology. Understanding it, therefore, comes down to learning its rules and intricacies. Designers, in this context, ultimately act as translators, and becoming fluent in the site's language is therefore an essential part of the design process. That is why must show up to the site with a dictionary in hand. We must become actively involved in it, talk to its users, experience it, read up on its history. Then, and only then, can we design *with* the site instead of just *for* it, enabling it to become involved as a stakeholder in the design process.

Not the be-all end-all

Upon understanding the site, it becomes immediately clear that there is no perfect approach to its preservation. What is more, though preservation can be achieved at a physical level with an architectural intervention, the true revival of a building - or, in this case, a village - will ultimately come down to a combination of approaches and a collaboration between agents from different disciplines and backgrounds.

Agrilia was abandoned after the Theran earth mines shut down in the 1940s. Its original residents and their descendants have built their lives elsewhere and most likely will never return. Therefore, the revamping and revival of Agrilia will have to target a different group of users. This is all determined by the broader context that Agrilia is a part of. At the end of the day, it is a small village in a small island that lives in the shadow of a tourist giant. But even Santorini's main island of Thira is still subject to the ebb and flow of Greek life and politics. Even more broadly, the whole Aegean sea is at risk from the implications of climate change. So, the revival of Agrilia will ultimately depend on the alignment of a series of factors that start from its survival within the environmental context of the 21st century, and end with the actual repair and reuse of the houses.

Zooming out so far, it seems ludicrous to assume that 3D printing could single-handedly achieve the revival of the village and, in fact, it can't. However, as we follow the chain of events that will ultimately lead to its revival, LSAM still plays a role somewhere down the line. Though this seems almost philosophical, understanding the tiny role that 3DP - or any technology, for that matter - plays in such a project was imperative in the process of coming up with an intervention.

There is a tendency, in innovation, to attribute every new, promising technology with a "holy grail status". We have seen this happen with Artificial Intelligence and Large Language Models whose abilities are overestimated. The excitement that comes with their discovery leads us to believe that they will solve all of our problems. The same is true for 3D printing; and, when tackling a project that investigates the opportunities for such a technology in a specific field, it is much too easy to assume that it should play a big role in it. Immediately, one starts thinking of large-scale applications that essentially take over the entire preservation process because the technology should be at the center of it. But this could not be further from the truth. In the case of Agrilia, it was experts from Boulouki that gave the first warning of this bias. They indicated over and over that 3DP should only play a small part in the process. It should only come into play where it truly has value.

They gave the example of their own practice: they focus on the preservation of traditional building techniques, and much too often they become blinded by the apparent heritage value of these traditional techniques that they forget to expand and build upon them. It is, in fact, for this reason that such a collective was even interested in 3D printing for heritage preservation in the first place.

This is what made the intervention so specific. Naturally, it had to be specific so as to produce a specific prototype as a proof of concept. But, as the intervention design process hopefully shows, it was also the result of a careful ommission of aspects of Agrilia where 3D printing should not intervene. In fact, before landing on architraves, the potential of LSAM as an intermediate step in the repair process through the printing of molds was even considered.

A holistic approach

Having learned the language of the site and understood the role that AM should play in its repair and reuse, we begin to see the intervention take form. Our approach to it as an intervention, however, cannot be limited to its design. As a real, physical project, it will not simply appear in place, but will need to be produced and assembled.

The analysis of Theran building techniques highlighted the importance of Theran earth as a building material and its processing as a form of intangible heritage. This provided an opportunity to integrate these into the intervention. Developing a holistic approach towards the intervention enabled us to see the opportunity of preserving this intangible heritage. First, by omission, by not intervening in parts of the houses where Theran vernacular techniques were the protagonists (such as the cisterns and stone paths), and then, in the design of the intervention; dividing the architrave into tiles not only made their production easier, but guaranteed the involvement of craftsmen in their assembly.

Earlier in the project we remarked how preservation is incredibly site-specific. Later, we saw that the heritage of a site can extend to non-material things, and that even these could be preserved through design. This only highlights the importance of the designer as a "master builder" in the process. Effectively, a translator between all these different disciplines; someone with knowledge of both digital and traditional craft, someone who can understand culture and history - their role in the heritage value of a site -, and someone who can understand its users.

Designers are jugglers, they are translators, they are facilitators and communicators. Ultimately, a complex, multi-faceted project such as this one provides the perfect opportunity to showcase this unique set of skills.

Project limitations

The project showed a number of limitations in its practical application, i.e., in the intervention design part. These were mostly based on the limitations of the technology, as well as the damage observed in the village of Agrilia.

Site-specific limitations

The site-related limitations relate to the applicability of the intervention to multiple cases of damage, as well as its integration with traditional building techniques.

The search for a case of damage was guided by the supposed parameterization of the intervention. By observing recurring cases due to the repeating typology of the houses, we would theoretically be able to fix multiple cases at once. While there were a number of damaged windows in the village, out of the 130 houses originally built in Agrilia, only a few of them still preserve their facades or interior walls. In the revamping of the whole village, the structural damage to the houses would have to first be assessed in order to choose which of the remaining facades could be kept in their current state and which ones would have to be taken down and rebuilt in the traditional way. The lack of resources available on site and the fact that no such assessment has been made as to the integrity of the houses means that we cannot be certain about the number of windows that could actually be repaired by applying this intervention approach.

Additionally, the intervention does not supplant any relevant craft existent in the island. However, it fits into the building process in a way that might be disruptive to the way craftsmen are used to working. More specifically, though houses in Agrilia in their current state present a unique materiality in their decay, it is possible that this decay will be accelerated without the proper application of plaster and limewash to the exterior walls of the houses. If the walls had to be plastered and painted, this would hide the 3D-printed tiles. While this would not affect their performance, it would warrant a redesign to account for the thickness of those superficial layers of plaster and paint. More importantly, this would eliminate the aesthetic impact of the intervention; it would be hidden inside the walls of the house and therefore would not be distinguishable from the original building fabric.

Technological limitations

The technological limitations of the intervention relate, firstly, to the fact that Theran mortar could not be printed using the facilities at LAMA and, secondly, to the geometry of the tiles themselves.

While the stoneware clay used in the experiments proved to resemble Theran mortar very closely in terms of its look and feel, its printing behavior is different. Assuming that Theran mortar behaves similarly to cement-based concrete when printed, the tiles might have to be printed with a larger nozzle than was available for the experiments. This might not imply a larger layer height but, if it did, the aesthetic impact of the tiles would have to be reassessed.

Stoneware is a very versatile printing material; yet, in some cases, it performs worse than concrete: mainly when printing with large overhangs. Some of the architrave's tiles feature relatively large overhangs. Now, this could be tackled in two ways: either experimenting with accelerants in the printing of Theran mortar (though accelerated concrete printing is very prone to cracks that could compromise the structural integrity of the architrave), or by making the surface of the tiles smoother and filling in the gaps with wet mortar. One of the reasons for which wet mortar was suggested for the assembly of the tiles was precisely this, as well as to eliminate any error caused by irregularities in the prints. Still, this is something that would need to be tested with the material on site.

Finally, it is important to mention the logistical limitations of assembling 30 tiles around a window gap. This is a problem that is often mentioned in literature. While it helps that the tiles are unique and therefore the "puzzle" is easier to solve, such a large number of tiles still presents a challenge in their assembly, especially as the project grows. The more windows we repair and the more workers we involve, the project slowly turns into a logistical nightmare.

Future steps

Some of the project's limitations could be addressed in future work. The time constraints of this project as a graduation thesis meant that some parts of it were developed superficially. The lack of facilities at the laboratory were the 3D printing experiments were done, as well as the short duration of the iterative design process left some aspects of it open for further iteration, evaluation, and implementation. These are detailed here.

On-site evaluation

One of the project's greatest limitations was the fact that the intervention could not be tested on the site. While Agrilia provided a uniquely interesting case study, it was difficult to access and a third visit did not fit into the project's timeframe.

A first step to guarantee the feasibility of the results presented here would therefore be to print and assemble a test architrave to assess the difficulties in its assembly, the logistics involved in the transport and printing of the tiles, the sourcing of the material, etc. Additionally, the aesthetic impact and continuity of the intervention could be truly evaluated. Far from a laboratory setting where results are not always reliable, seeing the architrave in its natural environment would certainly resolve many unanswered questions.

Further iterations

The time constraints of the project did not allow for much experimentation when it came to some of the aesthetic aspects of the intervention. Where there was aesthetic freedom, the design decisions were maded based our perception of the site and its aesthetic qualities. However, a number of aspects of the tile design could have been developed further. In a supposed continuation of the project, iterations on the infill of the tiles would need to be done, as there is a wide variety of geometries that can be used for this. Additionally, the surface texture could also be iterated on, especially after testing how the architrave fits in on site. Finally, windows with different dimensions could be integrated into the design, as well as additional design elements. This could include shelves on the inside or light fixtures on the outside. The possibilities that LSAM offers in the addition of these features are virtually endless, and there are certainly additional featues that could be integrated into this intervention.

Material testing

Finally, the tests done with Theran mortar were very limited. Following the advice of material experts involved in Boulouki's laboratory research, actually assessing the behavior of this mortar when 3D printed would require months of testing. For this reason, it was left out of the scope of the project.

Different ratios of Theran earth and lime would have to be tested, as well as their combination with accelerants to facilitate printing larger overhangs and taller objects in general. Their curing behavior would also have to be monitored; and so would the appearance of cracks on the tiles due to the material's shrinkage. Mechanical tests should be carried out to see if the tiles could support the weight of one another and their reaction to prolonged exposure to the sun and elements would give an answer to the previously posed question of whether or not to apply a layer of plaster and limewash on top of them.

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Appendix A: Project brief

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Nikolas Barrera Parisakis **Student number** 5,621,305

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Design explorations on the potential of large-scale additive manufacturing in the reuse of historic buildings

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

The preservation of cultural heritage (i.e., artefacts, buildings, monuments, etc.) has been benefiting from recent advancements in technology, particulary in the fields of documentation and conservation, for instance through Artificial Intelligence, Augmented and Virtual Reality, and 3D scanning. In particular, 3D printing is commonly used in aesthetically accurate restorations or replicas of artefacts and building fragments. However, this technology holds promise beyond its ability to accurately reproduce complex geometrical forms and details.

New requirements resulting from modern preservation guidelines have opened up opportunities in the additive manufacturing space, as the digitalization and parametrization of building models hints towards restoration workflows that incorporate digital fabrication techniques. This creates an opportunity for large-scale 3D printing to not only address the practical challenges of preservation in the built environment, but to create additional value through preservation efforts. Using parametric design, the original structures are integrated into CAD models and 3D-printed interventions can be simultaneously tailored to said original structures and adapted to introduce new, functional design elements that contribute to the modernization of historic buildings.

Additionally, additive manufacturing can be used to establish a new design language that is informed by tradition, yet enabled by contemporary craftmanship. Beyond merely replicating historic building fragments, 3D printing can allow for innovative material expression, which can enhance or reinterpret traditional values. The technology's ability to influence materiality, through parameters like layer height, texture, material, and form opens up a space for exploration of how such modern interventions can harmonize with the rest of the building. This project will attempt to strike a balance between restoration and innovation, where the new elements both respect and redefine the cultural identity of the structure, while creating additional value trough the addition of modern functional design elements.

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introduction (continued): space for images

image / figure 1

image / figure 2

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

The main problem being adressed in this project is that of the preservation and restoration of historic buildings. More specifially, of architectural details such as ornaments or sculptural facade elements that can benefit from the opportunities created by 3D printing. Such elements are constantly threatened by decay, environmental conditions, and poor conservation efforts. Traditional restoration techniques are often impractical due to various factors such as their high cost, the lack of skilled technicians and artisans with knowledge of traditional techniques, or the lack of traditional materials. This creates an opportunity for digital fabrication techniques to be incorporated into such conservation efforts. 3D printing can offer fast and efficient restoration, while replicating complex architectural details. At the same time, it can meet modern safety and sustainability standards, producing elements that can prolong the life of heritage structures not only because of their resilience, but also their ability to revitalize said structures through their modernization and adaptive reuse.
However, it remains unclear how 3D printing can seamlessly integrate into the preservation and adaptation of historic buildings. While the technology holds promise, the boundaries of its known possibilities in terms of shape, materiality, and compatibility with traditional craftsmanship must be pushed. This project will explore how 3D-printed interventions can respect and enhance the cultural identity of heritage structures, addressing critical gaps in current applications. Without a deeper understanding of how these modern forms can align with historical aesthetics, 3D concrete printing risks producing disjointed additions to heritage buildings rather than a harmonious continuation of their architectural legacies.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Investigate, in a site-specific case study, how large-scale 3D printing can be tuned to facilitate the repair and reuse of historic building fragments in a way that satisfies the guidelines of preservation and conservation, as well as enables the addition of integrated, functional design elements to make them suitable for modern use.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

The project will include a literature review on heritage preservation and the theoretical frameworks around it, with a special focus on the integration of digital fabrication into said preservation efforts. During the first phase of research, a case study analysis will be conducted in order to highlight gaps in current research and identify opportunities for the project. Interviews with experts on the preservation of heritage and digital fabrication techniques will be conducted, especially in the faculty of Architecture and the Built Environment. This preliminary research should converge in a site-specific application of 3D printing in heritage preservation. The rest of the project will be tailored to said site.

Further on, experimental research in the form of 3D-printed prototypes will be done using the facilities at the Laboratory for Additive Manufacturing in Architecture. This part of the research will feature iteration in the printing techniques used, experimenting with parameters such as printing materials, printing mediums and printbeds, nozzle geometries, variable layer height and width, coiling, patterns, and non-planar printing. In a final phase, the findings of the research will be evaluated next to traditional preservation techniques through performance evaluations, comparative analyses, expert testing and feedback, and sustainability assessment methods.

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	24 Sep 2024
Mid-term evaluation	21 Nov 2024
Green light meeting	28 Jan 2025
Graduation ceremony	25 Feb 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

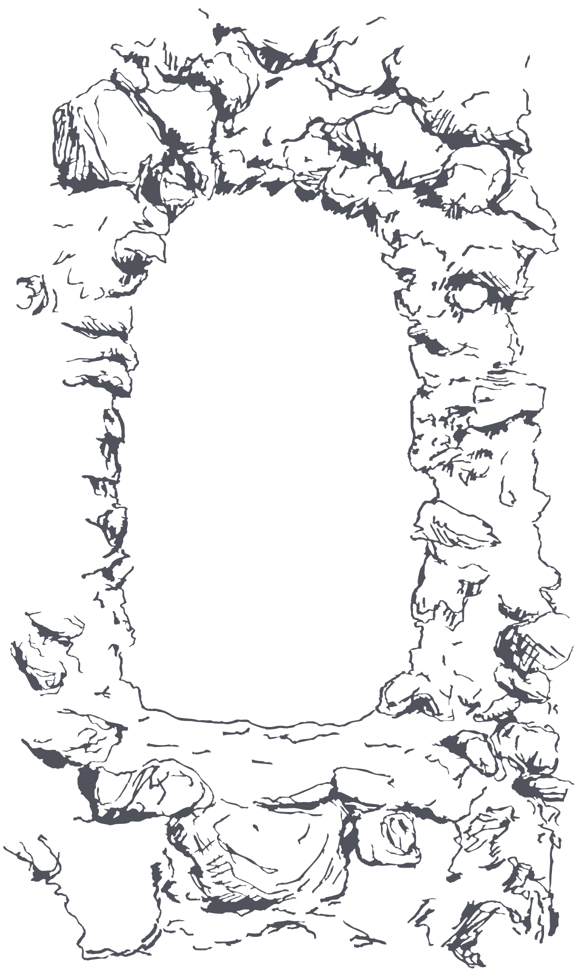
Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

My personal motivation for starting this project is to combine my passion for heritage preservation with my recent internship experience in large-scale 3D printing and expand on the knowledge I gained there. I want to experiment with 3D printing processes and apply them to a subject that I not only interests me personally, but that I believe could greatly benefit from 3D printing interventions. I would like to improve my parametric design skills and delve deep into the intricacies of additive manufacturing at a large scale. On a professional level, I want to further develop my project management skills, practice interpersonal communication skills when it comes to dealing with clients and external experts, as well as challenge my critical thinking abilities.



Layer by layer

Exploring Opportunities for Large-Scale Additive Manufacturing in Heritage Preservation

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