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ERASMUS MUNDUS JOINT MASTER DEGREE

**MASTER DEGREE IN SUSTAINABLE DESIGN, CONSTRUCTION
AND MANAGEMENT OF THE BUILT ENVIRONMENT**

MBUILD

PARAMETRICALLY-DESIGNED 3D-PRINTED EARTHEN WALL GEOMETRIES FOR IMPROVED THERMAL PERFORMANCE

RENZO CORCINO FELICIANO

Supervision: Prof. Bárbara Rangel (FEUP), M.Arch. MSc. Jaime Cunha (FEUP),
M.Eng. Sofia Pessoa (FEUP)

Porto, July 2025



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Dedicated to my family, friends, and everyone I've come across in this journey,
who all have helped me become who I am today.

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Hopefully this work can somehow contribute to the progress of 3DP and sustainable construction, not only in Europe but around the world.

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ABSTRACT

The construction industry significantly contributes to global carbon emissions and energy consumption. By 2050, its impacts are projected to increase by up to 50%, driven mainly by increased space heating and cooling. Literature suggests that one passive approach to reduce such impacts is the improvement of the thermal performance of the building envelope. 3D printing with earthen materials offers a promising approach to this, given its flexibility and capacity to create high-performance components from a globally available, low-carbon material with high potential for thermal performance. However, as current research focuses on structural and rheological properties of 3D printed earth components, there remains a critical gap in optimizing their thermal performance, specifically through geometric design. This study then aims to investigate and quantify how parametrically generated geometries in 3D-printed earthen walls can improve thermal performance. A state-of-the-art review first identified the primary principles that can influence thermal performance. This was then followed by the conceptualization and parametrization of three novel base geometries using Grasshopper and Rhinoceros, which were then systematically iterated into 20 variants and 5 optimized variants across 7 cm and 5 cm print layer thicknesses. Numerical simulations using steady-state 3D heat transfer analysis using TRmesh and TRfem plugins then quantified their U-values. A holistic multi-criteria evaluation using the MARS-SC method globally assessed the thermal performance, embodied carbon, and cost of the geometric iterations. Finally, initial insights on buildability were made through scaled 3D printing of selected designs.

Results showed that Geometry B consistently exhibited the lowest U-values among unoptimized designs, (whose U-values ranged from 0.82-1.65 W/(m²K)), mainly due to its narrow airspaces and the absence of direct thermal bridges. While 5 cm geometries generally outperformed 7 cm geometries, specific exceptions were observed, indicating the complex interplay of void size, air conductivity, and thermal bridging. While most initial designs did not meet stringent European U-value standards, optimizing the best-performing unoptimized geometry (5B-5) through modifying the earth mix used or adding cork insulation significantly improved thermal performance. The 5B-5 Low λ Earth 2 + Cork iteration achieved the lowest U-value of 0.13 W/(m²K), presenting a lower U-value than that prescribed by the Regulation on Energy Performance for external walls of new residential buildings for Batalha, Portugal. The multi-criteria assessment showed an inverse correlation between lower U-values and higher costs and embodied carbon. Further, the assessment identified 5B-5 with low conductivity earth as the overall best performer, highlighting that material improvements can offer more balanced solutions than relying solely on additional insulation. Finally, scaled 3D printing revealed Geometry C's excellent printability, while Geometry B exhibited stability challenges due to its unsupported design, emphasizing the need for integrated structural support.

This study demonstrates the potential of geometric design to improve the thermal performance of 3D-printed earth walls, showing that sustainability and high performance are achievable. At the same time, it stresses the importance of multi-criteria assessment for identifying the designs that best balance performance with practical and environmental considerations. This work is expected to contribute a methodology that combines natural materials with advanced fabrication methods to support the construction industry's decarbonization.

Keywords: 3D printing, earth walls, parametrization, thermal performance, geometry

GENERAL INDEX

ACKNOWLEDGEMENTS	i
ABSTRACT	iii
1. INTRODUCTION	1
1.1.CONTEXT	1
1.2.MOTIVATION	2
1.3.OBJECTIVES.....	2
1.4.METHODOLOGY	3
2. STATE-OF-THE-ART.....	5
2.1. INTRODUCTION	5
2.2. 3DP IN CONSTRUCTION.....	5
2.2.1.DEFINITION AND BENEFITS	5
2.2.2.PROCESS AND MATERIALS.....	6
2.2.3.CURRENT DEVELOPMENTS AND RESEARCH GAPS	7
2.3.3D-PRINTED EARTH (3DPE)	10
2.3.1.MOTIVATION FOR USING 3DPE.....	10
2.3.2.MATERIALS AND PRINTING PROCESS.....	11
2.3.3.CURRENT DEVELOPMENTS AND RESEARCH GAPS	12
2.4.THERMAL PERFORMANCE IN BUILDINGS.....	14
2.4.1.PASSIVE THERMAL AND ENERGY STRATEGIES THROUGH THE BUILDING ENVELOPE.....	14
2.4.2.PRINCIPLES AND PARAMETERS OF THERMAL PERFORMANCE IN BUILDING ENVELOPES	15
2.4.3.THERMAL PERFORMANCE OF EARTH CONSTRUCTION	17
2.5.THERMAL PERFORMANCE IN 3D-PRINTED STRUCTURES.....	18
2.6.THERMAL PERFORMANCE IN 3DP: TOPOLOGIES	20
2.6.1.HEAT TRANSFER IN COMPLEX TOPOLOGIES.....	20
2.6.2.CASE STUDIES IN LITERATURE.....	21

2.6.3.SYNTHESIS: IMPROVING THERMAL PERFORMANCE THROUGH TOPOLOGY	32
2.6.4.METHODS FOR MEASURING THE THERMAL PERFORMANCE OF 3DP COMPONENTS	40
2.7.CONCLUSIONS.....	46
 3. CASE STUDY.....	 47
3.1.METHODOLOGY	47
3.2.CONCEPTUALIZATION OF BASE GEOMETRIES.....	48
3.3.PARAMETRIZATION OF GEOMETRIES IN GRASSHOPPER	53
3.3.1.INTRODUCTION TO RHINOCEROS AND GRASSHOPPER.....	53
3.3.2.PARAMETRIZATION RULES AND INPUT PARAMETERS	53
3.3.3.GEOMETRY A: CLOSED CELL GEOMETRY	54
3.3.4.GEOMETRY B: MULTI-LAYER GEOMETRY WITH LONG HEAT PATH	58
3.3.5.GEOMETRY C: ALTERNATING SINUSOID AND STRAIGHT LAYERS	60
3.3.6.FINAL GEOMETRIES	62
3.3.7.ITERATION OF FINAL GEOMETRIES.....	62
3.4.NUMERICAL SIMULATION WITH TRMESH AND TRFEM.....	67
3.4.1.METHODOLOGY	67
3.4.2.RATIONALE FOR SOFTWARE SELECTION.....	70
3.4.3.TRFEM HEAT TRANSFER PRINCIPLES.....	70
3.4.4.TRFEM SIMULATION INPUTS AND OUTPUTS.....	71
3.4.5.VALIDATION OF TRFEM RESULTS.....	72
3.4.6.GEOMETRY PREPARATION IN RHINO	75
3.4.7.MESH GENERATION WITH TRMESH	75
3.4.8.SIMULATION SETUP	77
3.5.NUMERICAL RESULTS	79
3.5.1.U-VALUES.....	79
3.5.2.THERMAL OPTIMIZATION	83
3.5.3.HOLISTIC EVALUATION.....	87
3.5.4.OVERALL BEST PERFORMERS.....	101
3.6.3D PRINTING PROTOTYPES	104

3.6.1.METHODOLOGY.....	104
3.6.2.RESULTS.....	106
3.7 CONCLUSIONS	109
4. CONCLUSIONS	111
4.1. SUMMARY OF THE STUDY	111
4.2. RESPONSE TO THE PROBLEM STATED	112
4.3. PROPOSED OBJECTIVES/ACHIEVED RESULTS.....	112
4.4. RESULTS ACHIEVED IN EACH OF THE PREVIOUS CHAPTERS	112
4.5. CONTRIBUTION TO THE TOPIC’S BODY OF KNOWLEDGE	114
4.6. CONSTRAINTS OF THE PROCESS.....	115
4.7. FUTURE DEVELOPMENTS.....	116
5. REFERENCES	119
6. ANNEXES	129
A.1. ISOMETRIC IMAGES OF 3DP GEOMETRIC ITERATIONS	129
A.2. PREVIOUSLY CONSIDERED OPTIMIZATION OPTIONS	132
A.3. AIR CONDUCTIVITY COMPUTATIONS.....	133
A.4. GEOMETRY PREPARATION	135
A.5. COMMON MESH GENERATION ERRORS	136
A.6. SIMULATION SETUP (TRFEM READER AND C# CODE)	136
A.7. PARAMETERS FOR THE HOLISTIC EVALUATION	138

INDEX OF FIGURES

Figure 1 - Materials studied for use in 3DP construction elements.....	6
Figure 2 - Building components that have been studied for use in 3D-printed construction elements... 7	7
Figure 3 - Recycled and bio-based materials integrated in 3D-printed mortars.....	9
Figure 4 - Heat fluxes to and from a single-room building [58].	14
Figure 5 - Summary of thermal performance parameters in building envelopes. Adapted from Yu <i>et al.</i> [52]	15
Figure 6 - Printing parameters that can influence thermal performance of 3D-printed components [2].	19
Figure 7 - Heat transfer mechanisms through cellular structures [9].	20
Figure 8 - Heat transfer mechanisms through cavity walls [5].	21
Figure 9 - Thermal mass implementation on the interior side of the wall [14].	33
Figure 10 – Variant E, with the most void subdivisions at smaller sizes, possessed a lower U-value (1.27 W/(m ² K)) than variant D (1.54 W/(m ² K)) and variant A (2.17 W/(m ² K)) at the same wall thickness [26]. ..	34
Figure 11 - Left: Horizontally elongated cells [22]. Right: Vertically elongated enclosed cells [9].	34
Figure 12 - Horizontally closed-cell structures can improve thermal performance compared to open-cell structures [1].	35
Figure 13 - The diamond geometry outperformed the other geometries due to longer heat paths from exterior to interior [88].	35
Figure 14 - The several degrees of bifurcations (branching) in the TerraPerforma project [84].	36
Figure 15 - Double-row triangular and sinusoidal geometries exhibited lower U-values than their single-row counterparts [70].	37
Figure 16 - The undulations of exterior wall surfaces can positively impact thermal performance. Left: Digital Adobe [83], right: TerraPerforma [84].	37
Figure 17 – Potential complex 3DP geometries for improved thermal performance. Left: Sangiorgio <i>et al.</i> [7], right: Curth <i>et al.</i> [14].	46
Figure 18 - Methodological flowchart. (<i>Author's own</i>).	47
Figure 19 - Initial hand sketches of geometries. (<i>Author's own</i>).	49
Figure 20 - Sketch of geometry A. (<i>Author's own</i>).	50
Figure 21 - Sketch of geometry B. (<i>Author's own</i>).	50
Figure 22 - Sketch of geometry C. (<i>Author's own</i>).	50
Figure 23 - Sketch of geometry D. (<i>Author's own</i>).	51
Figure 24 - Sketch of geometry E. (<i>Author's own</i>).	51

Figure 25 - Sketch of geometry F. (<i>Author's own</i>).....	52
Figure 26 – Sketches of finalized geometric base options. (<i>Author's own</i>).....	52
Figure 27 – Overall Grasshopper script for geometry A. (<i>Author's own</i>).....	54
Figure 28 – Script inputs. (<i>Author's own</i>).....	54
Figure 29 – Part 1 of Grasshopper script for geometry A. (<i>Author's own</i>).....	55
Figure 30 – Part 2 of Grasshopper script for geometry A. (<i>Author's own</i>).....	55
Figure 31 – Part 3 of Grasshopper script for geometry A. (<i>Author's own</i>).....	56
Figure 32 – Part 4 of Grasshopper script for geometry A. (<i>Author's own</i>).....	57
Figure 33 – Part 5 of Grasshopper script for geometry A. (<i>Author's own</i>).....	58
Figure 34 – Overall Grasshopper script and inputs for geometry B. (<i>Author's own</i>).....	58
Figure 35 – Part 1 of Grasshopper script for geometry B. (<i>Author's own</i>).....	59
Figure 36 – Part 2 of Grasshopper script for geometry B. (<i>Author's own</i>).....	59
Figure 37 – Part 3 of Grasshopper script for geometry B. (<i>Author's own</i>).....	59
Figure 38 – Overall Grasshopper script for geometry C. (<i>Author's own</i>).....	60
Figure 39 – Part 1 of the Grasshopper script for geometry C. (<i>Author's own</i>).....	60
Figure 40 – Part 2 of the Grasshopper script for geometry C. (<i>Author's own</i>).....	61
Figure 41 – Part 3 of the Grasshopper script for geometry C. (<i>Author's own</i>).....	61
Figure 42 – Final base geometries. (<i>Author's own</i>).....	62
Figure 43 - Overview of all analyzed geometric iterations.....	63
Figure 44 – Screenshot of TRfem Grasshopper script.....	68
Figure 45 – Screenshot of TRfem inputs used.....	69
Figure 46 – Screenshots of TRfem reader and solver components.....	69
Figure 47 – Screenshot of TRfem isosurface component.....	69
Figure 48 – Sensitivity analysis for the number of isosurfaces.....	73
Figure 49 – Comparison of simulation results using the same mesh with different isosurface counts: 30 isosurfaces (left) and 15 isosurfaces (right), resulting to variations in the output.....	74
Figure 50 – The modeling geometry in Rhino: baked and prepared solid (left), and the resulting air breps (right).....	75
Figure 51 – Unified volume containing solid and air breps (left) and the resulting mesh from TRmesh (right).....	76
Figure 52 – Tetrahedral mesh with assigned boundary conditions: blue tetrahedra represent the exterior (cold) side, red tetrahedra indicate the interior (hot) side, and green tetrahedra correspond to adiabatic boundaries.....	76
Figure 53 – TRfem simulation inputs.....	77

Figure 54 – Screenshot of TRfem output values and mathematical operations to obtain the U-value...	78
Figure 55 – Sample isosurface diagrams: plan and isometric view.	78
Figure 56 – Bar graph showing U-values of all analyzed geometries vs. standards.	83
Figure 57 – Step-by-step optimization framework.	84
Figure 58 – Bar graph of optimized solutions U-Value results.	86
Figure 59 – The three main dimensions for holistic evaluation.	87
Figure 60 – U-value comparisons between 7 cm and 5 cm geometries.....	91
Figure 61 – Print volume comparisons between 7 cm and 5 cm geometries.	92
Figure 62 – Print time comparisons between 7 cm and 5 cm geometries.	93
Figure 63 – Cost comparisons between 7 cm and 5 cm geometries.....	94
Figure 64 – Void percentage vs U-Value.	94
Figure 65 – Print volume vs U-Value.....	96
Figure 66 – Cost for all analyzed geometric iterations.....	98
Figure 67 – U-value vs cost.	99
Figure 68 – Embodied carbon for all analyzed geometries.....	100
Figure 69 – U-value vs embodied carbon.....	101
Figure 70 – Dispatch, flip, and weave components.	105
Figure 71 – Termite plugin with inputs (printing speed used: 100 mm/s).....	105
Figure 72 – Excerpt of a sample g-code.....	105
Figure 73 – 3D printing parameters and results.	107
Figure 74 – Wall collapse of 3D-printed earth at the eighth layer of printing at long wall spans (left and center) (Courtesy: EcoMIT Project); Intermediate connectors (right) (Courtesy: Havelar).....	108
Figure 75 – Initial optimization loop using Wallacei/Galapagos. Was deemed infeasible due to limitations in the thermal performance plugin used. (<i>Author's own</i>).	133
Figure 76 – Three initial modeling options: geometry without side connectors (left), geometry with side connectors (center), geometry with full side walls (right).	135
Figure 77 – Self-intersections present in the geometry need to be removed by reparametrizing.	136
Figure 78 – Screenshot showing (1) TRfem mesh reader, where the mesh can be input, and (2) the C# component where Air BREPs can be input.....	137
Figure 79 – Developed C# script for the classification of tetrahedra.	138
Figure 80 – Sample photo showing the centroids of the tetrahedra classified as "solid" (highlighted in red) based on the C# classification script. All remaining tetrahedra (not highlighted) are classified as "air", and thermal conductivities are then assigned accordingly.	138

INDEX OF TABLES

Table 1- Constructed 3D-printed structures around the world.	8
Table 2 - 3DP geometries from constructed projects.	21
Table 3 - 3D-printed geometries from research articles.	24
Table 4 - Summary of topology design concepts for thermal performance.	38
Table 5 - Numerical simulations used by research articles to measure thermal performance.	41
Table 6 - Experimental tests used by research articles to measure thermal performance.	44
Table 7 – 3D images and dimensions of geometric iterations for simulation (units: meters).	64
Table 8 – Influence of edge length (e.l.) range on the simulation results for case 2, mesh 5 with the refined C# code.	73
Table 9 – Sensitivity analysis for number of isosurfaces.	74
Table 10 – Lower resolution mesh validation.	74
Table 11 – Finalized TRfem simulation settings and inputs.	75
Table 12 - U-values of the simulated geometric iterations.	79
Table 13 - Ranking of iterations based on U-value.	82
Table 14 - Summary of properties for low thermal conductivity 3DPE mixes.	84
Table 15 - Optimized U-value results.	85
Table 16 - Components of the evaluation dimensions.	87
Table 17 - Values and specifications of components.	88
Table 18 - Holistic evaluation results including optimized iterations.	89
Table 19 - Side-by-side comparison of 7 cm and 5 cm versions of the same geometries.	91
Table 20 - U-value comparisons between 7 cm and 5 cm geometries.	91
Table 21 – Print volume comparisons between 7 cm and 5 cm geometries.	92
Table 22 – Print time comparisons between 7 cm and 5 cm geometries.	93
Table 23 – Cost comparisons between 7 cm and 5 cm geometries.	94
Table 24 – Comparison between reference geometries and best and worst unoptimized cases.	97
Table 25 – MARS-SC method normalization and aggregation.	102
Table 26 – Ranking lists for the geometric iterations.	103
Table 27 – Isometric images showing 3DP texture and side connections at wall terminations.	129
Table 28 - Thermal resistance of unventilated air layers with high emissivity surfaces. [15].	134
Table 29 - Convective heat transfer coefficients for temperature differences larger than 5K. [15].	134

SYMBOLS, ACRONYMS AND ABBREVIATIONS

3D – Three-dimensional

3DP – 3D printing or 3D-printed

3DPC – 3D-printed concrete

3DPE – 3D-printed earth

AI – Artificial intelligence

AM – Additive manufacturing

CO₂ – Carbon dioxide

EN – European Standard

E-PLA – Expanded polylactic acid

EU - European Union

FEM – Finite element modelling

GHG – Greenhouse gas

GWP – Global warming potential

HFM – Heat flux meter

HVAC – Heating, Ventilation, and Air Conditioning

ISO – International Organization for Standardization

LCA – Life Cycle Assessment

MARS-SC – Methodology for the Relative Assessment of Building Solutions

PCM – Phase change material

PETG – Polyethylene terephthalate glycol

PLA – Polylactic acid

RE – Rammed earth

cm – Centimetres

K – Kelvin

kg – Kilograms

m - Meters

m² - Square meters

W – Watts

λ – Thermal conductivity

ρ - Density

1

INTRODUCTION

1.1. CONTEXT

The construction industry (CI) is a major global energy consumer and contributor to the world's carbon emissions, and its impacts are only projected to increase in the next decades [1]. According to Sovetova & Calautit [2], this sector represents about 34% of total global energy consumption and 21% of total global carbon emissions. By 2050, these contributions are predicted to rise by 20% to 50%, mainly due to increased space heating and cooling [2]. In addition to the concerns brought about by climate change, rapid population growth and increased time spent indoors have created a larger demand for energy use in housing and other building typologies, resulting in higher emissions and waste generation [2]. In the context of the European Union (EU), the European Commission [3] reports that the CI consumes 40% of the EU's energy and generates 37.5% of waste and 36% of greenhouse gas (GHG) emissions. These emissions stem primarily from construction processes, building operations, renovation, and demolition [1]. At the same time, the CI is often regarded as a low-tech sector that relies heavily on manual labor, seeing limited technological advancements in its processes and methods. Compared to other industries, which have become largely automated, construction has suffered from stagnant growth in productivity [4].

With these realities, there is a critical need to explore low-carbon and energy-efficient building solutions that minimize effects on the environment to respond to climate change. These solutions align with the concept of sustainable development, which according to Li *et al.* [5], requires innovative changes and initiatives in the industry. Energy-efficient buildings and the integration of renewable energy sources are being encouraged in projects to achieve the goal of carbon neutrality in Europe by 2050, as outlined in the European Green Deal [1]. Various governments have also prioritized energy conservation codes and international green building rating systems, such as LEED and BREEAM [6].

While the need is present, the CI has also demonstrated significant potential to catch up, demonstrated by various innovations in construction processes and methods. One of these innovations is 3D printing (3DP), also known as additive manufacturing. 3DP is recognized as a key technology in Industry 4.0 (the fourth industrial revolution) [7], and more specifically, Construction 4.0, which aims to transform the construction industry. It is touted as one of the most promising tools that can help provide a paradigm shift for construction process, going toward a more digital and sustainable approach [7, 8, 9]. The advent of this technology can have significant positive implications especially for project management [8], including increased productivity and improved overall efficiency.

1.2. MOTIVATION

3DP has emerged as an innovative manufacturing technology with the potential to revolutionize construction processes. This technology offers a host of benefits, including reduced greenhouse gas emissions, decreased material waste, and enhanced energy efficiency [10, 11]. Notably, 3DP provides a high level of design flexibility [12], enabling the creation of complex geometries difficult to execute with conventional methods, that can fundamentally improve various aspects of building performance, such as thermal efficiency.

Among 3D-printed materials, 3D-printed earth (3DPE) presents a highly sustainable option compared to the more commonly used cement-based mortars [4]. Earthen materials are characterized by low embodied carbon, local availability, recyclability, and inherent thermal mass properties that support passive temperature and humidity regulation [13]. This combination of properties positions 3DPE as a strong choice for addressing modern sustainability challenges in the built environment.

However despite recent advancements, significant research gaps still exist in fully understanding the effective thermal performance and energy efficiency of 3DPE structures. Specifically, there is a very limited number of studies focusing on 3DPE geometries and their thermal performance. Existing literature often indicates that the heat transfer coefficient (U-value) of 3DP components frequently do not meet current thermal performance standards unless additional measures, such as insulation, are introduced. This shows the need to explore and optimize more complex geometries in 3DPE walls to inherently enhance their thermal performance [14], thereby reducing reliance on additional, often carbon-intensive, measures that can undermine circularity. Furthermore, holistic evaluations of these components, that integrate thermal performance with other practical considerations such as cost, embodied carbon, and buildability are still yet to be explored deeply in existing literature.

As such, this study is motivated to address these identified research gaps by investigating how geometric complexity and design can be optimized to improve the thermal performance of 3DPE walls, while simultaneously considering their broader practical and environmental implications.

1.3. OBJECTIVES

This study aims to investigate and quantify the thermal performance of 3DPE wall geometries, ultimately providing insights for the development of highly performative and sustainable building envelopes. The primary objectives are the following:

- To identify the principal factors influencing the thermal performance of 3DP wall geometries. This was achieved through a comprehensive state-of-the-art review, which analyzed existing geometric strategies and thermal design concepts from built projects and research to establish foundational principles and highlight current research gaps;
- To conceptualize and parameterize novel base geometries specifically for 3DPE walls. These geometries were developed by reinterpreting and innovating upon thermal concepts identified in the literature. They were then translated into adaptable parametric models using Grasshopper within the Rhinoceros environment, enabling the systematic generation of multiple iterations with varying levels of geometric complexity;
- To conduct numerical simulations using steady-state 3D heat transfer analysis for each generated geometry. The primary goal of these simulations was to quantitatively determine the U-value of each wall iteration, allowing for a direct comparison of their thermal performance;

- To perform a holistic multi-criteria evaluation of the generated geometries, to identify the ones that best balance thermal performance (U-value) with practical considerations such as economy (cost) and sustainability (embodied carbon), using a quantitative methodology to provide a balanced understanding of their overall performance;
- To gain preliminary insights into the buildability of selected complex geometries. This involved printing scaled 3D models of selected geometries to assess the feasibility of their construction and to inform future larger-scale applications.

1.4. METHODOLOGY

The research began with a comprehensive state-of-the-art review aimed at identifying the primary factors influencing the thermal performance of 3D-printed wall geometries and highlighting existing research gaps. The review specifically focused on strategies for enhancing thermal behavior in 3DP building envelope components, cataloguing geometries and thermal concepts from both published research and built projects.

Building on these insights, three base geometries were conceptualized. These designs integrated and reinterpreted thermal principles identified in the literature, prioritizing feasibility, printability, and flexibility for iteration in the succeeding stages. Initial hand sketches were refined based on factors like design complexity, projected printing path, buildability, and suitability for architectural applications.

The finalized geometries were then translated into parametric models using Grasshopper within Rhinoceros. This parametrization facilitated a systematic iteration workflow and enabled a sensitivity analysis of design variables such as layer count, void size, and overall geometric complexity. The main conditions, including a fixed wall thickness of 40 cm and two print layer thicknesses (7 cm and 5 cm), were applied to ensure comparability in the simulation stage.

Subsequently, each base geometry underwent systematic iteration, resulting in multiple levels of geometric complexity. This process, which involved manipulating various parameters, generated 20 distinct wall iterations for simulation. Due to limitations in automation with the chosen software, parameter adjustments and result analysis were conducted manually.

Thermal performance was quantitatively assessed through numerical simulations to calculate the U-value of each iteration. Steady-state 3D heat transfer analyses were performed using the TRmesh and TRfem plugins in Rhino and Grasshopper. The simulation inputs, including air conductivities, were determined and validated in accordance with established standards such as UNE-EN ISO 6946:2021 [15].

Following the numerical simulations, a holistic, multi-dimensional evaluation of the results was conducted. This included benchmarking the simulated U-values against reference geometries and existing energy efficiency standards in Europe. The objective was to identify wall geometries that achieved an optimal balance between thermal performance (U-value) and practical considerations such as print path length, print volume, print time, cost, and embodied carbon. A quantitative assessment using the MARS-SC (Methodology for the Relative Assessment of Building Solutions) method enabled a global evaluation and ranking of each geometry across two defined weighting scenarios.

Finally, scaled 3DP of selected geometries was performed. The most complex geometries with 7 cm layer thickness were chosen for prototyping using clay, providing initial insights into their buildability. At the same time, the scaled prototyping served as proof-of-concept models for the designs and a basis for potential future experimental validation.

2

STATE-OF-THE-ART

2.1. INTRODUCTION

This state-of-the-art reviews the current literature on 3D printing (3DP) in construction, expounding on its benefits, materials, processes, current developments, and research gaps with a focus on 3D-printed earth (3DPE) and its thermal behavior. Further, it identifies and discusses the principles of thermal performance in buildings, and then emphasizes the unique factors that affect the thermal performance of 3D-printed structures. It then explores different 3DP topological designs, their impact on thermal performance, and existing research gaps, supported by case studies and research projects. Finally, it concludes by summarizing the geometric principles identified to improve thermal performance in 3D-printed structures.

2.2. 3DP IN CONSTRUCTION

2.2.1. DEFINITION AND BENEFITS

In construction, 3DP, or additive manufacturing (AM), has become an important topic in research and plays a crucial role in advancing the Construction 4.0 industry. Aligning with future sustainability goals by increasing productivity and minimizing material waste among others, it is seen as a novel strategy to revolutionize sustainable construction.

ISO/ASTM 52900:2021 [16] officially defines 3DP as a *"process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies."* Other authors add to this definition, describing 3DP as a process of developing 3D objects from digital designs under the control of a computer [17, 18]. Due to this digital control, 3DP makes possible the production of complex and non-standard elements, providing flexibility and adaptability to the construction process.

The sustainability of 3D-printed buildings has seen growing attention in research [5]. Literature reports that 3DP can provide opportunities for more sustainable construction through the following benefits:

- Decreased GHG emissions, as it eliminates a great amount of CO₂ emitting and energy-intensive processes, and optimizes construction processes and components [8, 10, 17];
- Reduced raw material waste and increased material efficiency compared to conventional methods, especially with the incorporation of recycled elements [10, 11, 12];
- Increased energy efficiency [11];
- Decreased environmental impact of material transportation by moving production directly to the construction site, if used onsite [11];
- Lower construction costs compared to conventional construction [12];

- Reduced use of formwork, labor force [12], and resource demands, as well as decreased human errors in the formwork construction process [10];
- Faster construction [10];
- Greater design flexibility, potentially through parametrization, allowing for more complex geometries, performance and multifunctionality [12, 19]. This performance could include building physics performance, such as thermal efficiency, with the introduction of performative geometries.

2.2.2. PROCESS AND MATERIALS

A 3DP system is primarily composed of a mixing unit, a pumping mechanism, an extrusion system (print head, nozzle), and a motion control system (gantry system, robotic arm, crane-based) [17]. At the same time, the printing material needs to meet certain property requirements, such as: (1) pumpability, indicating that it can be easily transported through the delivery system; (2) printability, meaning the material can be effectively deposited through the nozzle; and (3) buildability, referring to its ability to support required loads, resist deformation, and meet the necessary structural behavior of the build [17]. Though 3DP methods in construction vary, the primary focus of research and practical application in construction is the material extrusion method. This process involves continuously depositing a material layer over layer following a digital model. The mixture must be able to support its weight and the weight of overlapped layers, in order to produce a structure without deformations [17]. This thesis will focus on this method.

Today, the most common print materials in 3DP construction are cement-based mortars that often have a high proportion of fine aggregates to ensure that the material can go through the extrusion nozzle [4]. Aside from cement-based materials, other studies have focused on foam, geopolymer, clay, metal [2]; sand [12]; and even wood-based components [20]. Thermoplastics, such as polyethylene terephthalate glycol (PETG), polycarbonate (PC), or acrylonitrile butadiene styrene (ABS), have been studied to print façade prototypes [21]. Finally, earthen materials such as clay, cob, and lime-stabilized earth are also being studied as sustainable alternatives to cementitious mortars [13]. Figure 1 below shows a number of the mentioned studies. This thesis will focus on the use of 3DP earthen materials.



Lightweight concrete wall [9]



PETG façade [22]



Earth (sandy clay loam) wall [14]

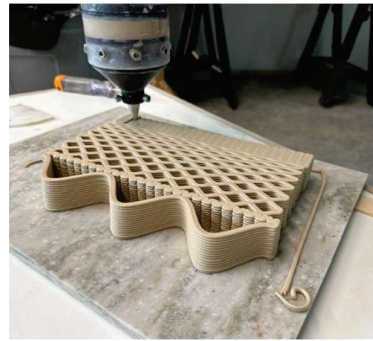


Wood-based (lignin, cellulose) window frame [115]

Figure 1 - Materials studied for use in 3DP construction elements.

2.2.3. CURRENT DEVELOPMENTS AND RESEARCH GAPS

In the context of construction, the scale of 3DP applications ranges from micro-components to large-scale structures and entire buildings [17]. Curth *et al.* [14] report that the most common large-scale 3DP structures are single-story houses made from quick-curing mortar. However, several other kinds of building components have been printed and studied, such as: walls [9, 14]; façade panels [21, 22]; blocks or bricks [14, 23, 24]; beams [2, 26]; window frames [27]; formwork [13, 21, 28]; and even furniture [20]. Figure 2 below shows some examples of these studied 3DP components.



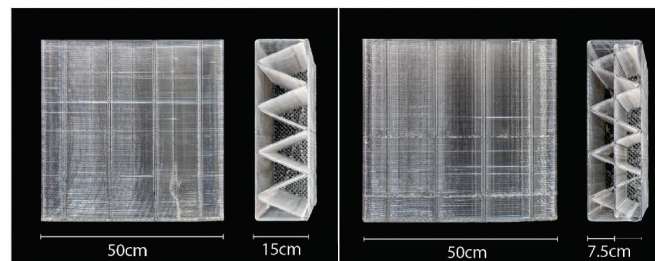
Clay brick [14]



Concrete column formwork [28]



Concrete beam [26]

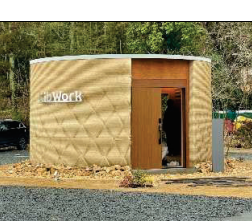


PETG façade panel [21]

Figure 2 - Building components that have been studied for use in 3D-printed construction elements.

Table 1 shows a catalogue of 3D-printed buildings already constructed around the world, referenced from literature. From the table, it can be seen that the majority of these projects fall under the house or pavilion typology, using either earthen or cementitious printing materials with various mix compositions, to create buildings from 10 m² to more than 1000 m². Additionally, most of these projects were initiated in developed countries such as the USA, Japan, and Italy.

Table 1- Constructed 3D-printed structures around the world.

Name	Typology	Material	Mixture	Image	Location	Year	Floor area
Gaia [29]	House	Earth	Soil, rice straw, rice husk, hydraulic lime		Massa, Lombarda, Italy	2018	~20 ~30 m ²
Casa Covida [30]	House (Sculpture)	Clay	Sand, silt, clay, water, straw		San Luis Valley, Colorado, USA	2020	14 m ²
Tecla [31]	House	Earth	Soil, water, rice husk, natural binder		Massa, Lombarda, Italy	2021	60 m ²
Dior Concept Store [32]	Temporary Pavilion	Clay	Clay, sand, raw fibers		Jumeirah Beach, Dubai, United Arab Emirates	2021	40 m ² / circle
TOVA [33]	Pavilion	Earth	Earth, water, sisal fiber, enzyme		Valldaura, Barcelona, Spain	2022	15 m ²
House Zero / Sunday homes [34]	House	Lavacrete	Cementitious-based mixture		Austin, Texas, USA	2022	185 m ²
TEIXIT [35]	Pavilion	Earth	Earth, water, organic fiber, natural enzyme		Valldaura, Barcelona, Spain	2024	-
Lib Earth House Model A [36]	House	Earth	Soil, lime		Yamaga City, Kumamoto Prefecture, Japan	2024	10 m ²

Sunday Homes at El Cosmico [37]	Hotel	Lavacrete	Cementitious-based mixture + sand & soil		El Cosmico, Texas, USA	Under construction	> 1000 m ²
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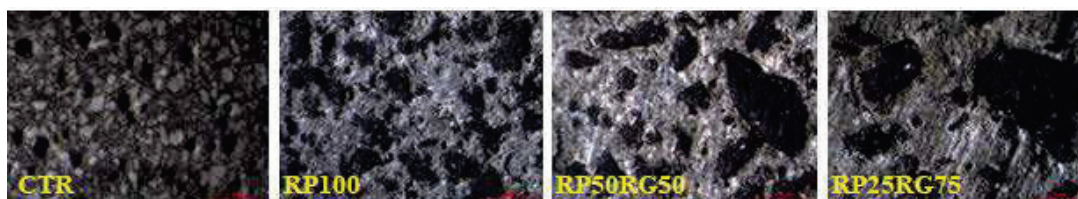
So far, research on 3DP has focused on print material development (e.g. extrudable mixtures), rheological properties of materials (e.g. pumpability, printability, and buildability), structural performance, process automation, and the exploration of complex geometries or forms [4, 38]. The use of recycled materials and industrial wastes, with the potential to increase the sustainability of 3DP, has also seen significant strides in research. There are several examples of reusing recycled fillers for cementitious materials, such as PET particles, wood chips, glass powder, and waste tire rubber aggregates [39]. Bio-based materials like natural fibers are also being studied to be integrated into mixtures [5], like earth [40]. Figure 3 below shows examples of these materials.



Light straw clay, light hemp clay, light kenaf clay, light banana clay [40]



Waste glass powder in geopolymers concrete [116]



Cement mortars with rubber [39]

Figure 3 - Recycled and bio-based materials integrated in 3D-printed mortars.

However, while advancements in technology are being made, 3DP construction is still in its early stages [41], and several research gaps are still present. For example, more research is needed to fully understand the life cycle performance of 3D-printed structures [25], particularly in terms of their long-term performance and durability. Related to this, life cycle assessments (LCA) currently lack consensus on the actual impacts of robots and equipment used in 3DP processes, with the type of energy source emerging as a significant influence [19]. Recent studies show that there is also great potential to further decrease

the environmental footprint of 3DP structures through alternative materials or approaches such as recycled wastes, supplementary materials, alternative matrices, functional hybridization, increasing energy efficiency of systems, and structural optimization [19]. Finally, there are also critical research gaps on performance aspects such as thermal and acoustic behavior [4]. Of the nine built projects listed in Table 1, only three make explicit mention of thermal performance considerations in their designs. *Tecla* [31], for instance, incorporates passive ventilation strategies in the wall's outer layer, insulation using rice husks to fill the inner cavities, and thermal mass achieved through the wall's infill geometry. Similarly, *Gaia* [29] employs natural ventilation in its external layer and thermo-acoustic insulation with rice husks in the inner cavities. *House Zero* [34], meanwhile, uses an unspecified insulation material and a proprietary cement-based mix called "Lavacrete," which adds thermal mass and slows down heat transfer into the interior. While these examples demonstrate different approaches to addressing thermal performance, most of the other projects do not provide any performance data or description of any thermal strategies. This highlights a gap in both the integration of thermal considerations, and the evaluation of their performance. Although research in this area is growing, significant opportunities remain to investigate and quantify thermal behavior in 3D-printed construction.

2.3. 3D-PRINTED EARTH (3DPE)

2.3.1. MOTIVATION FOR USING 3DPE

Tinoco *et al.* [19] reported that the environmental impacts of 3DP constructions, specifically those of 3D-printed concrete (3DPC) which are the most commonly built, are concentrated on cement (due to the high amount needed for proper rheology) and reinforcing steel. While using alternative cements and supplementary cementitious materials such as fly ash are encouraged to decrease environmental impacts, earth-based materials like cob are seen as promising alternatives since they do not use substantial amounts of chemical binders [19].

There have been studies highlighting the potential and viability of earthen materials in construction. Focusing on carbon impact, one study [42] indicated that unstabilized rammed earth and compressed earth blocks can effectively replace concrete for 1/5 of the carbon impact as nonstructural building elements, while simultaneously offering high thermal performance. In terms of structural building systems, a study [43] demonstrated the example of unstabilized, load-bearing raw earth systems up to 10 stories tall in Yemen, with compressive strengths from 1.5 to 4 MPa. It is still important to highlight, however, its difference with standard concrete (for instance C30/37, which has a compressive strength of 37.8 MPa [44]).

Often perceived as a primitive or low-quality building material [45] – and with building codes (such as the NMAC 14.7.4:2004 [46] in New Mexico or NZS 4298:1998 [47] in New Zealand) specifying minimum compressive strengths of adobe and rammed earth, suggesting the need for stabilizers to meet minimum strength requirements [14] – several studies believe that the potential of low-carbon materials like earth, clay, and cob should be explored more deeply in 3DP buildings. Earthen materials are uniquely suited for 3DP recyclable and low-cost structures, due to their worldwide availability, minimal carbon impact, and potential for structural and thermal performance [13]. With the advent of 3DP, addressing these challenges becomes possible.

Earthen materials are often available locally across the world, giving it the potential to be globally scalable and suitable to a wide range of climates. Below are the advantages of earthen materials, including 3DPE, as discussed in the literature:

- Earthen materials have **low embodied carbon**, especially compared to concrete, and with this the reduced depletion of natural resources [48]. The results indicate that similar to

rammed earth or compressed earth blocks, the embodied carbon of 3DPE is less than 1/5 of a 20 MPa concrete and 1/50 of a typical 3D-printed mortar [13];

- Unstabilized 3DPE can be **low-cost and directly recyclable or reusable**, meaning that failed prints or excess material can be directly re-integrated into the printing system if not yet dried or contaminated. Additionally, fully dried 3D-printed earth elements can be rehydrated and reused as well [14]. However, other sources explicitly state that earthen materials that are stabilized with cement cannot be directly recycled into new building material, as the chemical bonds created by cement hydration can damage the original properties of the soil [49, 50], thus making it significantly more challenging to segregate and reuse. Therefore, 3DPE's circularity largely hinges on the 3DPE composition, particularly if it contains non-natural stabilizers such as cement;
- In addition to structural benefits, they also have an **inherent fire-resistant nature** when their density is high enough. According to the German standard DIN 4102-1:1998 [51], earth (even with fibers) is not combustible if its density is higher than 1700 kg/m³ [14];
- Earth materials can also offer **high thermal performance**, as they have thermal mass properties for passive temperature regulation [13], as well as humidity regulation due to their absorption and evaporation abilities, which can promote a healthy indoor climate [52]. The investigation of Yu *et al.* [53] shows that rammed earth (RE) has a thermal storage coefficient (S) of 11.85 W/(m²·K), while that of aerated concrete is 3.10 W/(m²·K) for 300 mm x 300 mm x 30 mm blocks. The thermal storage coefficient is a parameter that quantifies a material's ability to store heat, with a larger value indicating a greater thermal mass performance. Although not strictly 3D-printed, this indicates that earth materials can better maintain the stability of indoor temperatures and therefore improve comfort compared to certain types of concrete;
- Using locally sourced earth can **reduce transportation costs** and therefore environmental impact, making it a localized and circular building process [13].

2.3.2. MATERIALS AND PRINTING PROCESS

Studies on 3DPE have used different earthen materials such as mud [14, 52], cob [48], and locally available soil [14, 54]. A number of the studied 3DPE materials are mixed with fibers (such as straw, rice husk, jute, coconut, sisal, or goat hair) or binders like lime or cement for stabilization [54].

According to Faleschini *et al.* [54], for 3DPE, the most suitable materials to use are the wet methods of earth construction. For this reason, they discuss that one of the most investigated materials is cob, which involves building monolithic elements with plastic earth mixes. Primarily, it is comprised of subsoil, straw, and water. Curth *et al.* [13] report that the soil used for any large-scale earthen construction project should have a suitable mix of clay and sand, or "sandy clay loam," with roughly 30% clay and 70% sand. This composition offers a good balance of workability, low shrinkage rate, and cohesion.

The mix design primarily needs to account for printability and buildability, requiring a balance between fluidity for proper extrusion without clogging, and enough viscosity to maintain the shape during printing [48]. Studies also show that particle size distribution, mixture ratios, fiber, and clay content have significant impacts in the compressive strength of earth mixes. These natural components can improve strength and durability, without sacrificing circularity of the mix [13]. For instance, Carcassi *et al.* [40] found that fiber-reinforced earth mixes can show up to 125% higher compressive strength compared to unreinforced clay soil-water mixes. Specifically, their unreinforced earth sample exhibited a compressive strength of 0.82 MPa, while all 3DP fiber-reinforced mixtures (with either straw, hemp, kenaf, or banana) achieved strengths of at least 1.07 MPa. The highest strength was possessed by the hemp fiber mixture, at about 1.8 MPa.

To 3D print earth, the following steps are prescribed by different studies:

1. Local soil first needs to be processed so it can be suited to the pumping system. Through field testing, soil with an appropriate ratio of clay to sand is first found. These field assessments often use visual examination [55] and then use simple deposition tests to assess soil composition. Common field tests mentioned in literature include manual sedimentation or shake tests [40, 48];
2. After drying, the soil is sifted to eliminate large rocks or organic debris to ensure pumpability [13]. Delgado and Guerrero [55] emphasize the importance of limiting the maximum size of particles in any earth mix, as large lumps may hinder uniform compression and create weak points in the component;
3. After this, the sifted soil is mixed with water and any additives such as chopped straw or additional sand to produce an extrudable and performative mix [13]. Ruckrich *et al.* [56], for instance, studied a mix with 55% fibers, 20% coarse sand, 25% clay, and 19% water;
4. Afterwards, the mix is to be left to sit for a specified amount of time to fully hydrate the clay, allowing it to reach a homogenous state, reduce material inconsistency, and ensure extrudability and pumpability for printing [13, 56]. Different sources state different resting periods, potentially due to differences in mix composition: according to Curth *et al.* [13], this period is 24 hours, while for Ruckrich *et al.* [56] it is one week;
5. This material is then loaded into the pumping system for printing afterwards [13].

If a print fails or certain extrusions are not needed in the finished structure (i.e. formwork or temporary supports), the material may be directly cycled back into the pumping system as long as they have not dried or been contaminated with rocks or concrete [13]. Gomaa *et al.* [48] explain that 3D-printed cob, for instance, can be reused after printing, either through the modification of a printed object (while still wet) or by trimming excess cob from already set elements, and introducing it back to the system.

In such a case that contamination occurs, it may be dried then sifted again before printing. In the case of prints that have fully dried, material may be rehydrated and then reused [13]. This demonstrates the fundamentally circular process of 3DPE.

2.3.3. CURRENT DEVELOPMENTS AND RESEARCH GAPS

3DPE buildings have been constructed in Spain, Italy, the UAE, and the USA, among others. As shown in Table 1, seven of the nine listed structures were built using earthen materials. WASP 3D-printed the first full-sized earth structure in Italy in 2018, after which the attention to 3DPE increased significantly [54].

Aside from construction projects, research on 3DPE has tackled, among other things, the following:

- material processing and mechanical characteristics of 3D-printed unstabilized earth: Perrot *et al.* [57] demonstrated that the compressive strength of 3DP mix (raw earth + water) in its hardened state could range from 1.22 MPa (circular nozzle), which is comparable to conventional cob earth material, to 1.65 MPa (square nozzle). The study, however, noted the slow hardening and strength development of the mix, which may present challenges to achieve high production rates. This is compared to the compressive strengths of concrete-based mortars (e.g. 10 MPa for a cork concrete mix, to 40 MPa for a sulfur concrete mix [17];
- printing parameters and geometric exploration: The findings of Gomaa *et al.* [48] revealed that for their 3D-printed cob mix, optimal printing occurred with an extrusion rate of 105-110% of the printer's motion speed, which provided a "ramming effect" that densified the layers and improved structural performance. In terms of geometric exploration, they found that unstabilized 3DP cob could handle straight inclinations of up to 40 degrees at a slow printing speed of 30 mm/s (without infill patterns) for 3-axis 3DP. Finally, they concluded that geometric

stability was influenced by the total footprint (as longer paths allow more drying time) and the balance between print speed and the material's hardening time;

- effects of lime binders and natural fibers on mechanical properties and printability: Faleschini *et al.* [54] discussed that lime binders generally resulted in lower mechanical strength (1.26 MPa) compared to cement binders (1.40 MPa) for 3D-printed earth-based mixes. They also found that natural fibers (0.5% coconut or sisal or goat hair) could significantly increase compressive strength by 27-37% and flexural strength by 56-65%. Additionally, they explain that short fibers, like rice husk, were the most effective in reducing shrinkage, achieving as low as 0.31%. However, they acknowledge that while fibers improve mix cohesion and stability, they also introduce challenges to extrudability;
- extrusion systems or nozzles: For example, Gomaa *et al.* [48] developed a new dual-ram extruder that improved the continuity, extrusion rate, and consistency of the 3DP cob printing process. The system could achieve an extrusion rate of up to 120 mm/s with a 45 mm nozzle, compared to the 5 mm/s limitation of earlier extruders. In addition, it featured two 8,000 ml cartridges for a total of 16,000 ml, and a consecutive reloading process which ensured continuous printing and reduced human intervention;
- Life cycle assessments (LCAs), to compare the impact of 3DPE with the impact of other construction methods: Curth *et al.* [13] investigated through an LCA that 3DPE has a significantly lower carbon impact (0.006 kgCO₂/kg) compared to 3DPC (0.208 kgCO₂/kg), fired clay brick (0.230 kgCO₂/kg), and even rammed earth (0.023 kgCO₂/kg). The study also notes that the energy required to pump the material is the main contributor to the climate impact in the 3DPE process; however, this impact was deemed still relatively low compared to conventional construction methods. In the study of Faleschini *et al.* [54], one optimized 3DPE mix (lime binder with sisal fibers) achieved an embodied carbon of about 0.052 kgCO₂/kg, compared with the carbon footprint for ordinary cement (0.930 kgCO₂/kg) and that of natural hydraulic lime (0.635 kgCO₂/kg);
- thermodynamic properties of 3DPE for performative passive performance of walls: Through design optimization of the wall's inner and outer geometry according to the site conditions of Valldaura, Spain, Dubor *et al.* [52], through solar radiation simulations, were able to maximize total incident radiation by more than 4 times in winter and minimize it by 70% in summer. At the same time, their "heat sink" infill geometry was able to achieve a temperature drop of 10 °C and a reduction in heat transfer time when compared to a standard wall geometry.

However, 3DPE is still in its nascency and is largely uncharacterized [13]. Gomaa *et al.* [48] suggest that there are still several unique challenges of using earthen materials in the available 3DP systems in the market, requiring more viability studies for large-scale applications [19]. Particularly, printing with local earth has its unique challenges, such as shrinkage, pumpability, extrusion consistency, and variable mechanical properties [13]. In addition, soils, even when extracted from the same site, may not be uniform in profile or composition. This may necessitate adjustments to the earth mix, which could entail experimenting on its composition through fine-tuning the amount of water (and additives, if needed) to create a usable mix, depending on the soil's specific characteristics.

Other critical gaps in 3DPE discussed by literature include detailing material processing and load bearing tests for 3DPE with minimally processed soil mixtures, studies on resistance to erosion and water intrusion, the lack of standardized testing regimes and building codes, and studies on the degradation of the 3DPE material's long-term degradation, durability, and end-of-life. In fact, the study of Curth *et al.* [13] reveals that up to 2024, there have been no inhabited 3DPE buildings that have been demolished or recycled, and this limits full "cradle-to-cradle" life cycle assessments.

2.4. THERMAL PERFORMANCE IN BUILDINGS

2.4.1. PASSIVE THERMAL AND ENERGY STRATEGIES THROUGH THE BUILDING ENVELOPE

About 40% of global energy consumption is linked to buildings, with 75% of that dedicated to heating and cooling [58]. On average, the energy usage in residential and commercial buildings increases by 1.5% per year, with heating, ventilation, and air conditioning (HVAC) systems making up the biggest share of the demand [59]. With this, one of the primary goals of modern construction is to design buildings with high thermal performances, to reduce energy consumption and waste during building use to curb emissions, as well as to enhance quality of life and occupant comfort [17].

According to Sadineni *et al.* [60], two distinct strategies can be applied to improve thermal performance and building efficiency: (1) active strategies, which include HVAC systems and artificial lighting, and (2) passive strategies. One way to approach passive strategies is by designing according to context and climatic conditions [17], which entails proper siting, defining the shape and exposure of the building appropriately [61], shading [6], and altering window to wall ratios to regulate light, heat, and ventilation [61].

Another way to achieve higher energy efficiency and occupant comfort passively is by ensuring the good performance of the building's exterior walls, or building envelope, as it greatly influences energy consumption and, consequently, GHG emissions [4]. In fact, according to [62], the building envelope plays a pivotal role in this, accounting for 50–60% of heat transmission. This can be done by using materials or elements that minimize heat flows between interior and exterior [61], such as by selecting appropriate thermal insulation materials [4], optimizing the structure of window frames [27], or optimizing solar gains to lower energy demand [60]. Optimizing building envelopes through design and materials is then critical to minimize heat flows and reduce energy consumption, making its improvement an economical way to increase energy efficiency in the construction sector. Figure 4 below schematically illustrates heat flows through the envelope of a single room building, showing that heat fluxes can occur through both horizontal (floor and roof) and vertical (wall) building enclosures. At the same time, ventilation, infiltration, and heat gains from exterior sources such as the sun, and interior sources such as lighting, equipment, and occupants, have an influence on the thermal environment inside a building or space.

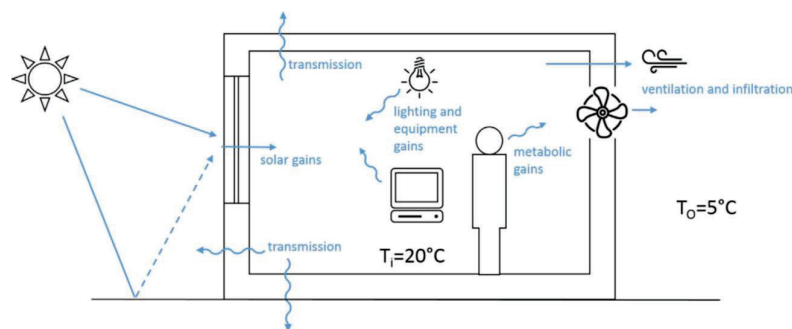


Figure 4 - Heat fluxes to and from a single-room building [59].

If designed accordingly, buildings can passively achieve improved energy performance and thermal comfort for building occupants. However, if needed, supportive and renewable energy systems can be employed afterward to reach even lower, or even zero-energy buildings [17].

2.4.2. PRINCIPLES AND PARAMETERS OF THERMAL PERFORMANCE IN BUILDING ENVELOPES

There are several principles and parameters related to the thermal performance of a building envelope. Below are the most prevalently studied in the literature. Figure 5 gives a visual summary of these parameters.

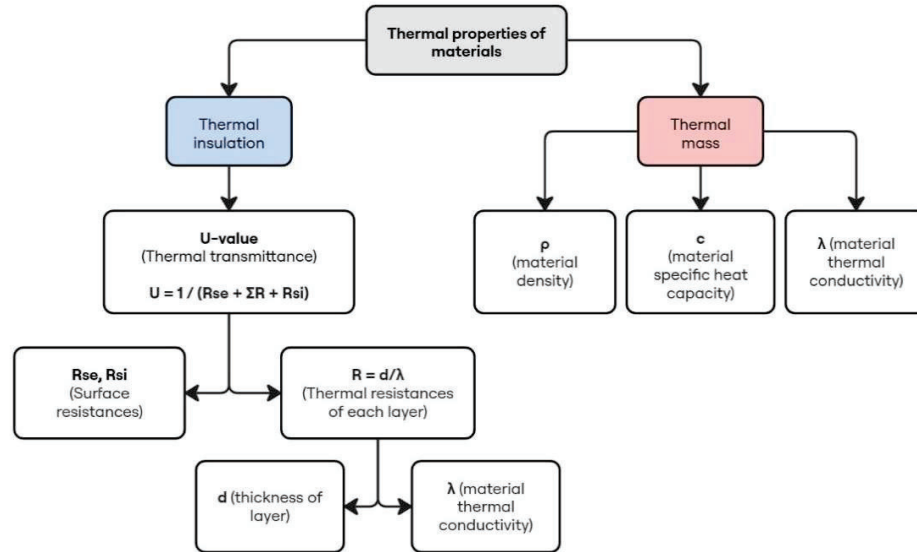


Figure 5 - Summary of thermal performance parameters in building envelopes. Adapted from Yu *et al.* [53]

Thermal insulation. A building's energy performance is mainly linked to energy losses through heat transfer across the envelope. Therefore, thermal optimization of the envelope should aim to reduce its thermal transmittance (U-value) and increase its thermal resistance (R-value). This can be achieved by using insulation with low thermal conductivity [63]. For buildings in heating-dominated climates, applying thermal insulation in building envelopes to increase thermal resistance is generally known as the most crucial way to reduce energy demand [59].

Thermal transmittance (U-value). The heat flux through a multi-layer component due to a temperature gradient [20]; a lower value indicates better insulation performance, and it is generally preferred when the goal is to reduce heat transfer [14]. Standard unit: $W/(m^2K)$. To illustrate, different countries have different U-value standards: In France and England, for example, regulations mandate new walls to meet a maximum U-value of $0.30 W/(m^2K)$ [64]; Germany: $0.28 W/(m^2K)$, Spain: $0.37-0.8 W/(m^2K)$, and Finland: $0.204 W/(m^2K)$ [65].

Thermal resistance (R-value). The inverse of the U-value [4]. The R-value is comprised of surface resistances R_{se} (exterior) and R_{si} (interior), as well as the design thermal resistances of each layer of material. The surface resistances account for the heat transfer between the wall's surfaces and the ambient air (or internal air) [20]. Higher R-values indicate more effective insulation and increased thermal inertia, impeding heat transfer [6, 11]. Standard unit: $(m^2K)/W$.

Thermal conductivity (λ). A material's inherent ability to conduct heat resulting from a temperature difference [4]. Lower values indicate superior insulation and reduced heat loss or gain within the building [6]. Standard unit: $W/(mK)$.

Thermal mass. Thermal mass, which is a building's ability to store heat energy as either sensible or latent heat, significantly impacts energy efficiency as it influences indoor temperatures, power requirements, and occupant comfort. It is an important concept for transient heating and cooling, which is the dominant thermal mode for buildings worldwide. There are three contributors to the thermal mass of a structure as a whole: the envelope and structural elements; the air volume; and fittings, furniture and other objects [66].

A building with a large amount of thermal mass in its envelope will display a reduced and delayed reaction to sudden changes in external ambient temperature. In other words, it is able to time-shift (progressively release heat depending on the temperature difference with the surroundings) and flatten out heat flow fluctuations. This transient behavior is known as the thermal inertia of a building [59]. The amount of heat stored depends on the following parameters:

- ρ - density of the material (expressed in kg/m^3);
- c - specific heat capacity of the material (expressed in $\text{J}/(\text{kgK})$);
- λ - the rate of heat exchange is influenced by the material's thermal conductivity.

High thermal mass is often presented as a positive feature of buildings and structures [66] as they maintain indoor comfort and reduce energy demand. Many case studies also prove its benefit in reducing overheating risks, as seen in medieval churches and vernacular architecture in hot climates, such as rammed earth buildings and earthships [59].

However, its general effects are not yet well-researched and quantified. It has been studied that thermal mass is not always beneficial with respect to occupant comfort and energy consumption. For example, Reilly & Kinnane [66] discuss that in the case of intermittent building use, which requires preheating and precooling to reach set point temperatures, higher thermal mass might result in thermal discomfort and increased energy use due to prolonged heating or cooling periods. Another example is in heavy-weight buildings, wherein adding more thermal mass has negligible effects.

Studies give evidence that the order of layers in a structure also results in significant impacts on the dynamic heat transfer. Generally, for most buildings and climates, larger amounts of thermal mass on the interior side of the thermal insulation improve thermal comfort and reduce energy demand [59]. For instance, Kossecka & Kosny [67] concluded that from an energy standpoint, a wall with all massive layers on the inner side and directly exposed to the interior space, is the preferred option in USA climates. These configurations were characterized by a low internal-to-external temperature amplitude ratio (0.047), which relates to improved thermal stability and minimum annual heating and cooling demand. Conversely, configurations with insulation on the interior side result in the largest energy demand, with an amplitude ratio of 0.222. The difference in total annual energy demand between the most and least efficient configurations is an average of 7.6% for a continuously used residential building, across different US climates.

Thermal inertia. Thermal inertia is defined as a material's property that expresses the degree of slowness with which its temperature reaches that of the environment [68]. At the same time, it can be interpreted as a measure of thermal mass and the speed with which a heat wave is transmitted through a material. Because of this, it is common to find references that directly call thermal inertia thermal mass.

Thermal inertia influences building behavior in the following ways [4]:

(1) in winter, it determines the building's ability to utilize solar gains for heating. During this time thermal losses must be less than gains, and so the incoming heat flux and power of equipment must be determined to maintain a constant indoor temperature;

(2) in summer, affecting its ability to absorb temperature peaks. During this time, thermal losses must be greater than thermal gains and therefore there is a need to control the outgoing heat flux to prevent exceeding certain temperatures.

Unlike thermal insulation which can be characterized by thermal resistance or transmittance, thermal inertia is not quantified by a single parameter – different indicators have been used by different researchers, such as thermal diffusivity, thermal admittance, and the time constant (which captures the combined benefits of a low U-value and a high heat capacity [14]). Different studies tend to conclude that additional thermal inertia in a building can increase occupant comfort and reduce energy demand, although some unfavorable cases, especially non-residential buildings in a warm climate, have been studied as well. However, the exact contribution of thermal inertia is difficult to quantify – for instance studied impacts on energy demand have seen results ranging from +10% to -80% [59]. This wide range is attributed to different factors, such as: (1) the varying nature of heat flows and climate over time, especially daily outdoor temperature and solar radiation, which influence the results; (2) a lack of standardized metrics and definitions of thermal inertia across studies, shown by authors using different parameters like thermal mass or thermal diffusivity; (3) different research methodologies employed, such as in-situ measurements versus analytical approaches versus simulation tools, which can also have different settings and computation methods; and (4) differing scopes of analyses, ranging from individual walls to whole buildings, which can also have different typologies such as residential and office buildings with distinct characteristics. This, therefore, makes it difficult to compare results.

2.4.3. THERMAL PERFORMANCE OF EARTH CONSTRUCTION

According to Curth *et al.* [14], earth has been traditionally used in construction in temperate and hot desert climates due to its high thermal mass properties, which allow buildings to dampen indoor air temperature fluctuations and simultaneously prevent excessively high indoor temperatures [69]. Furthermore, its high time constant value, which entails sufficient interior thermal mass and exterior insulation, allows for implementing pre-heating and pre-cooling strategies that reduce loads on electric grids. Traditional rammed earth structures, for example, usually 300 mm to 600 mm thick [53], use this significant thermal mass to absorb and store heat during the day, and release it during cooler periods, contributing to improved interior comfort.

According to the reviewed studies, the thermal conductivity of traditional earthen materials can range from 0.86 W/(mK) (traditional cob) to 0.09 W/(mK) (traditional light straw clay) [40]. Studies on the thermal conductivity of 3DPE mixes have also been performed. A study by Gomaa *et al.* [48], for example, examined the thermal performance of 3DP cob with different soils, finding that their thermal conductivity values can range from 0.30–0.50 W/(mK). Further, the study of [40] showed that 3DPE mixtures with fibers can achieve even lower thermal conductivities: 0.18 W/(mK) for light kenaf clay, 0.20 W/(mK) for banana clay, and 0.12 W/(mK) for light straw clay. These are all lower than the values of other 3DP mortars (e.g. 0.70 W/(mK) for a 3DPC mortar [70]) and conventional concrete (1.74 W/(mK) [53]). Materials with low thermal conductivity impede heat flow more effectively than those with higher conductivity, which are more prone to acting as thermal bridges. This highlights the potential of earth as a thermally performative material for construction applications.

Studies also show high potential specific heat capacity values for earth, equating to higher heat storage capabilities, directly contributing to a higher thermal mass. In the study of Carcassi *et al.* [40], specific heat capacity ranged from 3.37 kJ/(kg K) for the 3DP light straw clay, to 1.20 kJ/(kg K) for the 3DP light hemp clay. Compared to the concrete in one study [53], which had a value of 0.92 kJ/(kg·K), and of a 3DPC mortar with 1.127 kJ/(kg·K) [71], the earth materials mentioned have a larger contribution to a higher thermal mass, potentially benefitting thermal comfort and energy efficiency.

Additionally, the moisture regulation properties of earth materials like cob and rammed earth have been studied for interior space, as their absorption and evaporation abilities can promote occupant comfort and indoor health [72, 52]. For instance, the simulation performed by Yu *et al.* [53] shows that the high

moisture adjustment capacity of rammed earth materials can mitigate condensation, even at high temperature and dewpoint differences of 3–5 °C.

These properties demonstrate the importance of investigating ways to leverage earth in construction projects, especially those that can combine modern technology (such as 3DP) and vernacular building concepts, as ways to mitigate and adapt to climate change.

2.5. THERMAL PERFORMANCE IN 3D-PRINTED STRUCTURES

While considerable research on 3DP structures has been developed on material, structural and rheological characteristics [2], there is a significant research gap in its effective thermal performance and energy efficiency [4]. Nevertheless, with the industry's growing shift toward more sustainable practices, there is now an increasing focus on the thermal performance and energy efficiency of 3DP structures [2]. Existing literature shows that 3DP has the potential to improve a building envelope's thermal performance through different design strategies. Studies suggest that the main factors that can influence, and therefore potentially improve, the thermal properties of a building envelope through 3DP include the following:

- (1) **Material.** Optimization through the material, which can be done by modifying the material's structure (i.e. regulation of the porosity), composition (i.e. reducing conductivity), or the material type itself (i.e. using unconventional materials for insulation or using different materials in conjunction) [63].

Several researchers are investigating the alteration of print material composition, especially focusing on the aggregate density and mixture ratio [5], with the goal of improving thermal performance while using less material and reducing weight. For instance, Araujo *et al.* [73] 3D-printed lightweight cementitious composites with expanded clay aggregate instead of traditional fine aggregates, decreasing the 1.19 W/(m·K) thermal conductivity value to 0.68 W/(m·K) with the 100% replacement. Sambucci and Valente [39] investigated the use of recycled tire rubber aggregates in 3DP cement mortars, finding that the lightweight and non-polar nature of rubber improved the thermal insulation and structural properties of the material. Hao *et al.* [74] studied the effects of integrating paraffin, a phase-change material (PCM), into the recycled fine aggregates of 3DPC, finding that it can result in improved thermal performance that reaches up to 31% lower thermal conductivity compared to mould cast concrete. At the same time, research is ongoing regarding the incorporation of insulation materials within 3DP building elements. An example is the study by Suntharalingam *et al.* [71] who studied 16 different wall geometries with expanded polylactic acid (E-PLA) infill insulation, concluding that U-values could decrease by around 60-70% in certain geometries when adding infill insulation to otherwise empty air voids.

- (2) **Printing parameters.** The printing process plays a significant role in determining a 3DP structure's thermal properties, as it affects factors such as void formation, interlayer gaps, and microstructural differences. These factors contribute to thermal bridges and heat losses in 3DP samples [2]. For instance, Stepashkin *et al.* [75] found that 3DP polymer specimens demonstrated a 25-30% lower thermal conductivity value compared to cast specimens, which they attributed to the presence of voids and defects due to the printing process. Hao *et al.* [74] also reported that one of their printed samples possessed a 9.88% lower thermal conductivity than their cast sample (1.176 W/(mK) vs 1.305 W/(mK)), owing the difference to layered structures and interlayer voids. Further, they found that under the same size, density class, or mix design, the thermal conductivity of 3DPC with optimized printing parameters can be up to

31.04% lower than that of mould cast concrete. Sovetova & Calautit [2] discussed that the following factors can affect 3DP thermal performance (as summarized in Figure 6):

- **extrusion rate**, which is the rate at which material is deposited, affects anisotropy of thermal conductivity, amount of interlayer voids, and interlayer bonding. Higher extrusion rates can reduce interlayer voids, while lower extrusion rates can lead to poor interlayer bonding. As these affect thermal properties, an increase in extrusion rate can result in increased thermal conductivity due to higher density, lower porosity, and improved interlayer adhesion;
- **printing speed**, or the speed of movement of the printing head, affects microvoid formation and bead width. A higher printing speed can result in decreased bond strength among interfaces, reducing thermal resistance. At the same time, a higher printing speed can result in rougher surfaces, which can resist heat flow and potentially improve insulation performance. According to Sovetova & Calautit [2], increasing printing speed by 20% decreased thermal conductivity by 21% in 3DP concrete structures;
- **Nozzle standoff distance**, or the distance between the nozzle and the last deposited layer, influences interlayer bonding. Increasing this distance can lead to poorer interlayer bond strength and therefore affect thermal resistance;
- **Nozzle type/shape** can also affect thermal performance. Ramakrishnan *et al.* [76] investigated the use of customized nozzles to create hollow-core extrusions, which they found to have high thermal inertia due to increased insulation capacity;
- **Printing direction**, or the orientation of the deposited layers, influences the layer alignment, void and gap formation, and overall microstructure, impacting thermal conductivity. Printing in different directions can lead to anisotropic thermal conductivity (i.e. heat transfer can vary based on the direction of heat flow). Heat flow can either be more resistant or more conductive based on layer orientation. For instance, a study showed that samples printed using a rectilinear path showed a 16.4% lower thermal conductivity compared to a concentric path, with the difference being due to rectilinear paths possessing higher porosity than concentric ones [2];

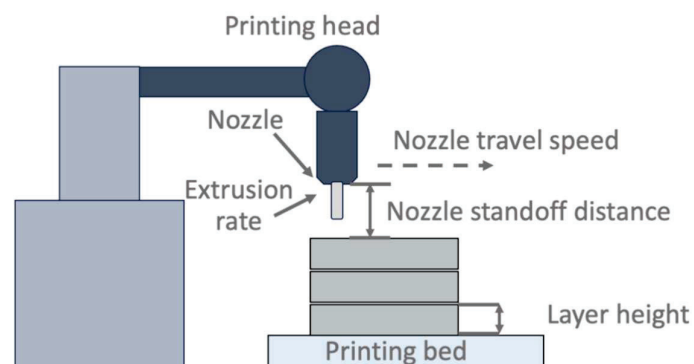


Figure 6 - Printing parameters that can influence thermal performance of 3D-printed components [2].

- (3) **Topology.** The final factor that can improve the thermal performance of 3DP structures is topological optimization, which involves modifying the internal or external geometry of the wall. Usually, this means increasing the geometric complexity of the component by adding more internal cavities and reducing their size, among other strategies [63]. This thesis focuses specifically on this strategy, as detailed below in Section 2.6.

2.6. THERMAL PERFORMANCE IN 3DP: TOPOLOGIES

2.6.1. HEAT TRANSFER IN COMPLEX TOPOLOGIES

3DP enables the construction of complex internal topologies (or geometries) that are difficult to achieve with traditional methods [77]. This capability offers several benefits, such as (1) reduced weight; (2) minimized use of raw materials; (3) energy savings [78]; (4) the ability to realize intricate shapes and customized structural forms [79]; and (5) improved adhesion of different elements, such as thermal insulation, plaster, or screeds, to the corrugated structure of printed walls [80].

Besides these benefits is the focus of this thesis, which is improving thermal performance through topology optimization. This direction was chosen for several reasons. First, it can address significant gaps in existing research (detailed in Part 2.7), such as the limited number of studies on the thermal behavior of 3DPE geometries, or the typical non-compliance of their performance with energy standards. With these, there remains a wide potential for innovation in this area, not only within the context of 3DP, but also for broader construction methods that might necessitate good passive thermal performance. Second, optimizing geometry can offer compound benefits, such as enhanced thermal behavior, while simultaneously reducing material usage, cost, and embodied carbon.

According to Bruggi *et al.* [61], topology optimization consists of determining the optimal distribution of material over a fixed domain, to maximize the performances of a body under a fixed set of constraints. With its capabilities and the design freedom it affords, 3DP through topology optimization can enhance thermal performance and energy efficiency in building envelopes while reducing weight through the adjustment of infill geometry and proportions [81, 82]. Furthermore, the flexibility of 3DP affords designers the opportunity to optimize elements to eliminate further treatments for energy reduction. Presented below is an introduction to heat transfer mechanisms in such geometries.

Among others, biomimetic geometries such as cellular or lattice structures, known for their lightness, stiffness, and excellent thermal and acoustic properties [4], are prime examples of designs that apply the above concepts. Such components with complex geometries may experience simultaneous heat transfer processes, namely conduction, convection, and radiation, due to the presence of both solid material and air cavities. Conduction occurs both within solid material and air cavities, while both convection and radiation occur only within air cavities [2, 83]. Figures 7 and 8 below show the different mechanisms of heat transfer through cellular structures and cavity walls, respectively. In 3D-printed cellular structures specifically, heat transfer involves convection and radiation within the cell. The conventional method of inserting insulation material within air gaps can greatly reduce convection and radiation effects; however, an alternative approach to reduce reliance on additional insulation material is to use only air to fill the cells to reduce heat transfer. Due to its low conductivity, air acts as an insulator in the static state, as in closed cells; however, in the dynamic state, it can accelerate heat transfer due to convection [2, 5].

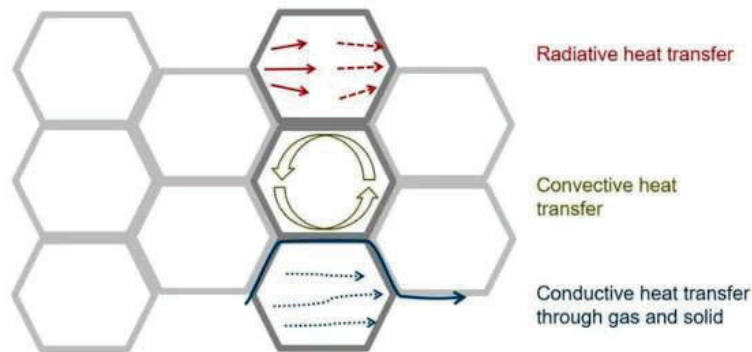


Figure 7 - Heat transfer mechanisms through cellular structures [9].

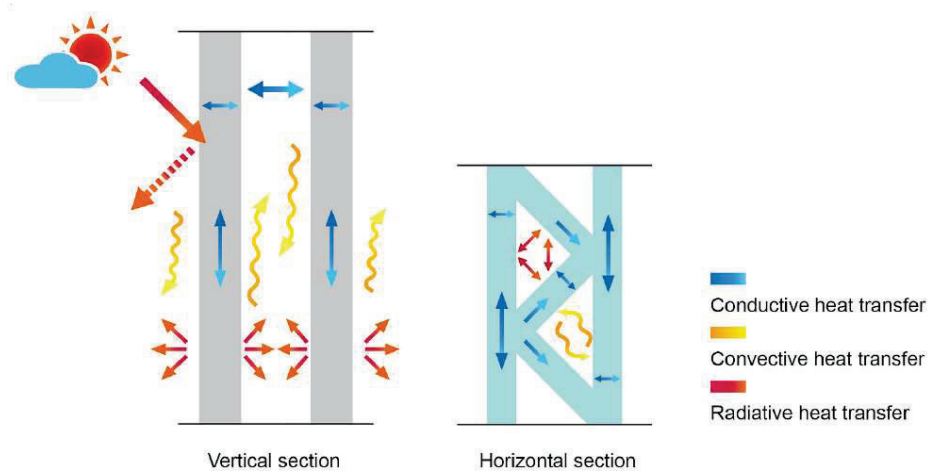
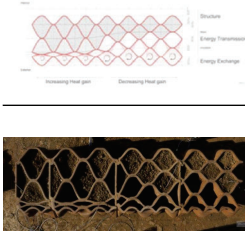
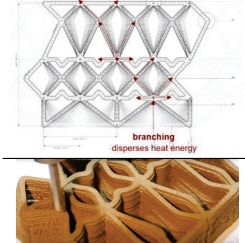


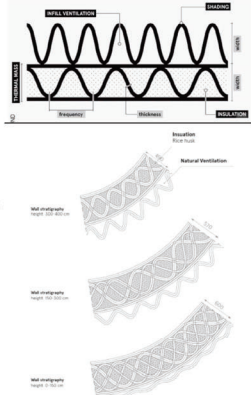
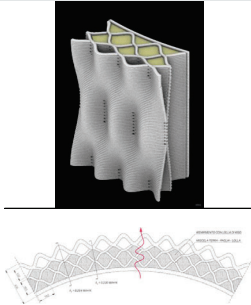
Figure 8 - Heat transfer mechanisms through cavity walls [5].

2.6.2. CASE STUDIES IN LITERATURE

A thorough literature review was performed to investigate the existing research on different 3DP geometries, vis-a-vis their relationship to thermal performance. Table 2 below shows 3DP geometries from built projects, while Table 3 features geometries from research papers, whose thermal performances were tested through numerical simulations and/or experimental campaigns.

Table 2 - 3DP geometries from constructed projects.

Study & Location	Typology & material	Insulation	Geometry/topology	Thermal concepts applied	Component & layer thickness	U-value (W/(m ² K))	Numerical simulation	Experimental test
Digital Adobe, 2018 (Spain) [117]	Brick/wall Clay (clay, water, aggregates, bio-based additives)	Earth		1. Bumps: self-shading during summer and maximum radiation during winter 2. Thermal mass: earth-filled cavities at interior 3. Insulation: hermetic air-filled cavities at exterior 4. Trombe wall concept	Component: bottom: 70 cm top: 20 cm Layer: 3.5 mm	not specified	not specified	Loading test, coating test
TerraPerforma, 2022 (Spain) [85]	Brick/wall Clay (sand, clay, water)	N/A		1. Self-shading during summer and maximum radiation during winter 2. Branching patterns for thermal lag 3. Closed air pockets for insulation	Component: 35 cm Layer: 3 mm	not specified	Rhino CFD (wind), Ladybug (sun), Karamba (structural)	Hygrothermal Monitoring Apparatus and Load Machine
TOVA, 2022 (Spain) [33]	Pavilion Earth (earth, water, sisal fiber, enzyme)	N/A		1. Cavity ventilation (east) 2. Modulated light filtration (south)	none specified	not specified	not specified	N/A

Study & Location	Typology & material	Insulation	Geometry/topology	Thermal concepts applied	Component & layer thickness	U-value (W/(m ² K))	Numerical simulation	Experimental test
Tecla, 2021 (Italy) [86]	House Earth (soil, water, rice husk, natural binder)	Rice husk		1. Thick wall with multiple layers 2. Sinusoidal cavities filled with insulation 3. Thermal mass - "ribbing" of the infill geometry 4. External "waves" as shading and ventilation chambers	Component: bottom: 60 cm top: 49 cm Layer: 12 mm	not specified	N/A	N/A
Gaia, 2018 (Italy) [87]	House Earth (soil, rice straw, rice husk, hydraulic lime)	Rice husk		1. Multiple layers 2. Sinusoidal cavities filled with insulation 3. External "waves" as shading and ventilation chambers	Component: 40 cm Layer: not specified	0.249	N/A	N/A
Lib Earth House Model A, 2024 (Japan) [36]	House Earth (soil, lime)	N/A		1. High wall thickness 2. Multiple layers 3. Sinusoidal cavities	Component: 48 cm Layer: not specified	not specified	N/A	N/A

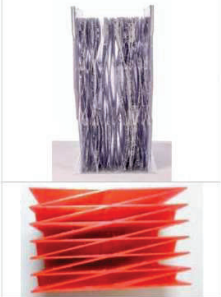
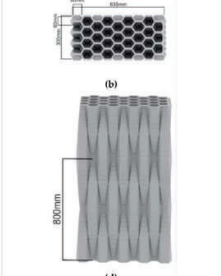
(1) The Digital Adobe project [84] utilized a sinusoidal geometry for its clay walls, incorporating **exterior bumps** that facilitate self-shading during summer and maximize radiation during winter. These bumps are hermetically air-filled to act as **exterior insulation**, while its interior cells are filled with earth to increase **thermal mass** at the interior side. (2) TerraPerforma [85] applied the concept of **branching patterns** featuring several degrees of bifurcations, to introduce thermal lag. At the same time, it used rhombus exterior geometries for shading and air pockets for insulation. (3) TOVA [33] takes the orientation of the building into account, by employing different solutions to different sides. For instance, the wall on the east side featured air cavities for insulation to respond to the projected solar gain, while modulated light filtration strategies in the form of wall openings were applied to the south-facing wall. (4) Tecla [86] and (5) Gaia [87] employ similar concepts of having ventilation chambers on the exterior and insulated cells (both with rice husk) on the interior side. Tecla employs thermal mass through the **ribbing** of its infill geometry, with more closely spaced ribs corresponding to higher thermal mass. This project features two main layers of waves, which can be tailored to different climatic conditions by increasing or decreasing parameters (such as wave frequency) with respect to others. (6) Finally, the Lib Earth House Model A [36] made use of a **high wall thickness** (48 cm) with multiple layers of sinusoidal and curved geometries.

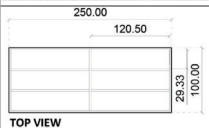
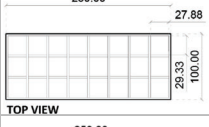
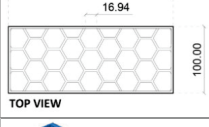
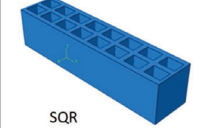
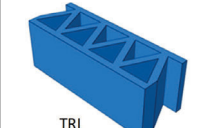
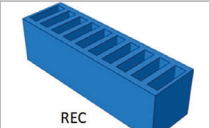
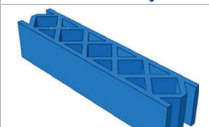
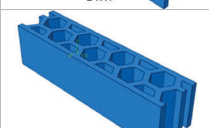
The majority of wall geometries featured in the analyzed projects made use of sinusoidal wave geometries in several layers. One reason for this could be the continuous print path that the wave allows [14], enabling a faster and more seamless printing process by minimizing the need for repeated stopping and starting of the extrusion process. Additionally, the layered wave geometry naturally creates multiple air voids and facilitates close control of their size, shape, and position. Further, when applied to the exterior face of the wall, this undulating texture can modulate solar exposure by increasing or decreasing shading, as mentioned above.

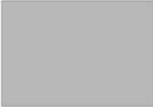
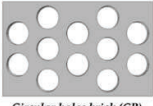
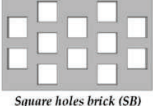
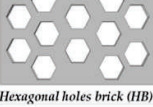
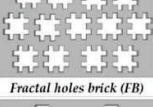
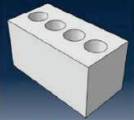
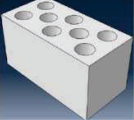
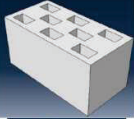
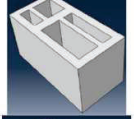
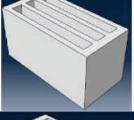
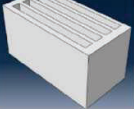
Most of the studied walls are thick, averaging around 45 cm in depth, with a number of designs tapering in thickness from bottom to top for structural stability. This substantial thickness, especially when featuring multiple intermediate rows, can contribute to increasing thermal performance by reducing overall thermal transmittance [71].

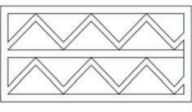
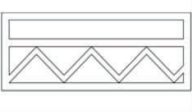
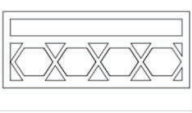
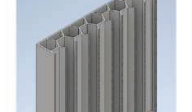
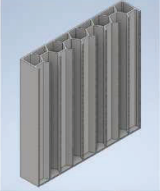
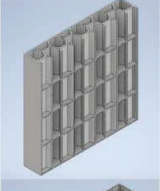
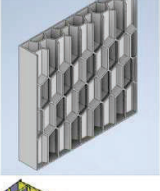
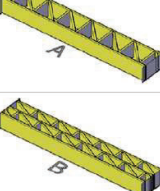
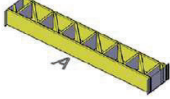
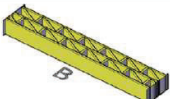
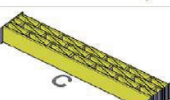
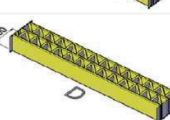
It was observed that while certain 3DP projects do mention qualitative thermal considerations in their designs (see Section 2.2.2), most built projects do not provide data on their thermal performance, especially regarding the U-value. This makes it difficult to assess the actual impacts of the building element's geometry on its performance. Notably, Gaia was the only project to provide a quantified measure of its walls' U-value, at 0.249 W/(m²K) (average). This was achieved by having air-filled cavities in its outermost layer and filling the two inner layers with rice husk (acting as a thermo-acoustic insulation). This, along with the high-performing floor and roof elements, allowed the house to be catalogued in Italy's energy class A4, indicating a low energy consumption and high energy performance [29].

Table 3 - 3D-printed geometries from research articles.

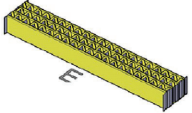
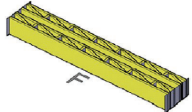
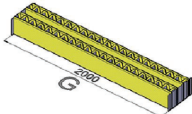
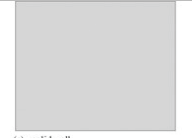
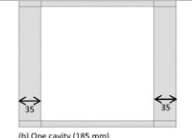
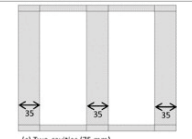
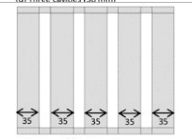
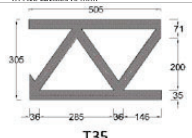
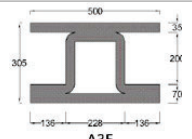
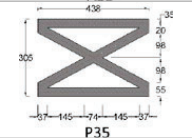
Study	Typology & Material	Thermal conductivity (W/(mK))	Geometry/topology	Thermal concepts applied	Component & layer thickness	U-value (W/(m²K))	Void %	Numerical simulation	Experimental test
Curth et al. 2023 [14]	Wall Earth (Sandy Clay Loam with <30% clay)	not specified		1. Optimized distribution of material across the section for thermal mass. Gradient in void structure - smaller air pockets on the interior side (to increase heat capacity where it is more needed) that gradually become larger on the exterior side (to reduce needed material)	Component: 50 cm Layer: 3 cm	0.51 - 0.59	not specified	Python-based components in Grasshopper (thermal) Kaleidoscope: Embodied Carbon Design Tool	N/A
	Brick Clay (medium fire stoneware clay)	not specified		2. Air pockets for insulation 3. Intricate geometries for longer heat conduction paths 4. [Wall] Insulation layer for column to prevent thermal bridging 5. [Brick] Outer shell as a ventilation chamber	Component: 15 cm Layer: 4 mm	1.25 - 1.35	not specified		
Bruggi & Taliercio 2013 [61]	Brick Concrete	not specified		1. Staggered pattern for longer heat path (few web connections) 2. High void percentage 3. Mechanical "core" at the center	Component: 30 cm Layer: minimum 2.5 mm	0.526	52%	Finite Element Analysis (code/algorithm; no software specified)	N/A
Sarakinioti et al. 2018 [22]	Façade panel PETG (thermoplastic polyester)	not specified		1. Closed cellular structures with low surface area (low solid to gas ratio) 2. Elongated cavities in all directions except the direction of heat transfer 3. Adaptable heat storage using a pumped water-based liquid	Component: 33 cm Layer: not specified	0.3	not specified	TRNSYS Dynamic Simulation	Hot Box heat flux test
Briels et al. 2022 [9]	Wall Concrete	0.38		1. Closed cellular structure 2. Low surface area/volume ratio 3. Vertical cell elongation 4. Low relative density	Component: 30 cm Layer: 12 mm width, 9 mm height	0.58	48%	THERM (2D) Computer Code S1; FCMLab (Finite Cell Method) (3D)	Heat flow meter method (ISO 9869-1:2014) Calibrated and guarded hot box (ISO 8990:1994)

Study	Typology & Material	Thermal conductivity (W/(mK))	Geometry/topology	Thermal concepts applied	Component & layer thickness	U-value (W/(m ² K))	Void %	Numerical simulation	Experimental test
Suntharalingam et al. 2021 [71]	Wall Bound sand	0.2		1. Cavity structures 2. Multiple rows/layers	Component: 20 cm Layer: 25 mm	1.74	49.7%	ABAQUS Finite Element Model (3D heat transfer analysis)	N/A
						1.26	63.1%		
						1.71	53.4%		
						1.01	21.7%		
						2.17	43.8%		
						1.01	36.4%		
de Rubeis et al. 2022 [88]	Brick/block PLA	0.28		1. Smaller cavity structures to reduce heat exchange 2. Multiple rows/layers 3. Complex geometry	Component: 10 cm Layer: 1.75 mm	1.43	not specified	THERM	Hot Box: Heat Flux Meter (HFM) and Infrared Thermography (IRT)
						1.25			
						1.22			
AlZahrani et al. 2022 [89]	Wall Concrete	0.371		1. Distance of heat transfer 2. Existence of branches	Component: 20 cm Layer: not specified	0.655	48%	ABAQUS Finite Element Model	N/A
						0.73			
						0.85			
						0.61			
						0.65			

Study	Typology & Material	Thermal conductivity (W/(mK))	Geometry/topology	Thermal concepts applied	Component & layer thickness	U-value (W/(m²K))	Void %	Numerical simulation	Experimental test
Sambucci and Valente, 2021 [39]	Brick Cement with Rubber	0.427		1. Complex hole shapes for thermal attenuation	Component: 150 mm Layer: 10 mm	2.86	40%	Heat Transfer in Solids Module of COMSOL Multiphysics 5.4	Printability test; Bulk density; permeable porosity; thermal conductivity and heat capacity; material properties, not geometry
						1.54			
						1.52			
						1.52			
						1.20			
						1.47			
			«Hybrid» brick (HFB)						
Al-Tamimi, 2017 *not 3D-printed; as reference only for geometric studies [83]	Brick Concrete	0.72		1. Staggering of holes 2. Number of barriers 3. Thickness of webs 4. Shape of holes 5. Hollow ratio	Component: 200 mm Layer: N/A	Interior Temp.: 29.53 °C	22.10%	ABAQUS	N/A
						29.21 °C	28.30%		
						28.92 °C	28%		
						28.39 °C	45%		
						28.29 °C	51%		
						28.29 °C	51%		
						28.16 °C	51%		

Study	Typology & Material	Thermal conductivity (W/(mK))	Geometry/topology	Thermal concepts applied	Component & layer thickness	U-value (W/(m²K))	Void %	Numerical simulation	Experimental test
Nemova et al. 2022 [70]	Wall Concrete	0.7		1. Air cavities 2. Number of barriers 3. Longer heat paths	Component: not specified	0.89	not specified	ANSYS CFX	Climatic chamber; Thermal Imaging
					Layer: 35 mm	1.05			
					Component: 35 cm	1.15			
					Layer: 35 mm	1.25			
					Component: not specified	1.59			
					Layer: 35 mm	1.59			
de Rubeis et al. 2024 [1]	Blocks PLA	not specified		1. Horizontal partitions and vertical translation of cells 2. Geometric complexity	Component: 100 mm Layer: 3 mm	1.22 (vertical)	not specified, but constant air volume	N/A	Hot box method, heat flux meter (HFM) sensors, infrared thermography (IRT)
						1.13 (horizontal)			
						1.18			
						1.08			
Cuevas et al. 2023 [10]	Wall Lightweight Concrete	0.46		1. Closed chambers/partitions	Component: 30 cm Layer: 2 cm	approx. 2.17	72.50%	LBNL THERM	N/A
						1.89	62.50%		
						1.69	52.20%		
						1.54	54.60%		

Parametrically-designed 3D-printed earthen wall geometries for improved thermal performance

Study	Typology & Material	Thermal conductivity (W/(mK))	Geometry/topology	Thermal concepts applied	Component & layer thickness	U-value (W/(m ² K))	Void %	Numerical simulation	Experimental test
Cuevas et al. 2023 [10]	Wall Lightweight Concrete	0.46		1. Closed chambers/partitions	Component: 30 cm Layer: 2 cm	1.27	39%	LBNL THERM	N/A
						1.92	66%		
						1.52	50.40%		
Marais et al. 2021 [90]	Wall Lightweight foam concrete	0.37		1. Narrow, parallel cavities	Component: 200 mm Layer: 35 mm	Interior Temp.: 21.40 °C	0%	ABAQUS	N/A
						22.76 °C	approx. 72%		
						21.87 °C	approx. 59%		
						21.42 °C	approx. 44%		
						21.15 °C	approx. 31%		
						20.98 °C	approx. 18%		
Chamatete and Yalçinkaya 2024 [11]	Wall Concrete	0.979		1. Void size and percentage	Component: 305 mm Layer: 35 mm	3.485	58.4	Ansys Workbench	N/A
						3.472	57.1		
						2.77	53.2		

Parametrically-designed 3D-printed earthen wall geometries for improved thermal performance

(1) Curth *et al.* [14] 3D-printed a clay brick and an earth wall section, integrating a sinusoidal geometry with a gradient in void structure and thermal mass. Their design was finalized using a multi-objective optimization tool, which cycled through different iterations to optimize parameters such as cell shape. Ultimately, they achieved a U-value range of 0.51 to 0.59 W/(m²K) for the 50 cm thick wall, and 1.25 to 1.35 W/(m²K) for the 15 cm thick brick, attributing their good performance to **air pockets for insulation, long thermal conduction paths, and optimized material distribution for thermal mass.**

(2) Bruggi & Talercio [61] improved the thermomechanical performance of 3DPC blocks through topology optimization. The study found that the U-value can be decreased by using **staggered layouts**, which lengthen the path that heat must flow to cross the wall and mitigate the existence of thermal bridges, since there is no straight element that connects the two sides of the wall. For their square block, the conventional staggered design had a U-value of 0.586 W/(m²K), but through optimization (exhibiting even more staggering), it achieved a U-value of 0.556 W/(m²K), equating to a 5% decrease. Similarly, **fewer webs along the wall thickness** and a **higher void percentage** were found to decrease transmittance as well. For instance, the U-value of square blocks decreased from 0.707 to 0.619 W/(m²K) when the number of connections between the exterior walls of the block and the internal core was decreased.

(3) Sarakinioti *et al.* [22] designed a PETG thermoplastic 3D-printed façade panel that integrated insulation with heat storage. Their design incorporated **closed cellular structures with low surface area and low solid-to-gas ratio**, and **elongated cavities** in all directions except the direction of heat transfer.

(4) Briels *et al.* [9] 3D-printed a concrete wall with a tetrakaidecahedron cell shape (U-value of 1.37 W/(m²K)), which was then optimized to have a 0.58 W/(m²K) U-value, considering a thermal conductivity of 0.38 W/(mK). In this study, cell structures were treated as a homogenous or bulk material, characterized by an average, or effective, thermal conductivity. The optimization was aimed then at minimizing this effective conductivity, by adjusting geometric parameters, to reduce the U-value. They pointed out that a **lower relative density**, or the ratio of solid to air inside the cells, is the main driver for reducing the equivalent thermal conductivity of the cellular solid, considering the lower conductivity of the gas. The optimization process found that structures with a **relative density of 0.2** minimized heat transmission (versus the printed version, which had 0.31). Additionally, the optimization led to the determination of ideal dimensions for the following parameters: **aspect ratio (or the ratio of the cell height to the cell diameter or size): >2, cell diameter: 70 mm, cell height: 800 mm, and cell wall thickness: 12 mm.** These were identified as the other factors involved in reducing the effective thermal conductivity of the cell structure, which was the fundamental means by which the U-value could be improved. Reduced internal heat transfer directly contributes to a better overall thermal performance.

(5) Suntharalingam *et al.* [71] assessed 16 3DPC wall geometries without cavity insulation, of which eight 200 mm single- and double-row geometries were chosen for this study, through finite element heat-transfer simulations. Their results highlighted the impact of the number of rows and intermediate barriers on thermal performance. According to the study, U-values generally decreased in **double-row designs** compared to single-row geometries. For instance, using a bound sand mixture with a thermal conductivity of 0.20 W/(mK), the U-values of double-row triangular geometries were 42% lower than the single-row versions. Similarly, double-row sinusoid geometries had a 41% lower U-value than their single-row counterparts. However, they found that the uninsulated cavity walls exhibited high U-values (ranging from 1.01 to 2.17 W/(m²K)), **failing standard regulations.**

(6) De Rubeis *et al.* [88] experimentally measured the U-values of three 3DP PLA bricks with different geometries (multi-row, square, and honeycomb), concluding that **U-values decrease as the internal geometry becomes more complex and the air cavities become smaller.** The honeycomb structure, the most complex, possessed a U-value of 1.22 W/(m²K). Conversely, the multi-row, which is the least complex, had a U-value of 1.43 W/(m²K). However, they found that the blocks exhibited U-values that are **still distant from those of commonly used insulation materials.** For example, standard insulation

materials such as expanded polystyrene with graphite (10 cm thick, $\lambda = 0.031 \text{ W/(mK)}$) had a U-value of $0.29 \text{ W/(m}^2\text{K)}$, while mineral wool (10 cm thick, $\lambda = 0.039 \text{ W/(mK)}$) had a U-value of $0.37 \text{ W/(m}^2\text{K)}$. This highlights that although geometry optimization can improve performance, they are not yet equivalent to conventional insulation materials. The study, however, suggests that filling the air cavities with insulation could further enhance their performance, potentially making them comparable to, or even better than, polystyrene-filled blocks.

(7) AlZahrani *et al.* [89] analyzed seven 3DPC wall infill structures, selecting five unreinforced ones for comparison: triangular, square, hexagonal, rectangular, and diamond. Finite element modeling (FEM) revealed that **increasing the heat path distance** and **integrating branches** reduced U-values. For instance, with a thermal conductivity of 0.371 W/(mK) , the diamond infill had the longest heat path and therefore the lowest U-value ($0.61 \text{ W/(m}^2\text{K)}$), while the rectangular infill had the shortest path and the highest U-value ($0.85 \text{ W/(m}^2\text{K)}$). In total, the U-values of their 3DPC walls were lower than conventional wall constructions, showing an enhanced thermal performance. For example, conventional concrete brick walls had a U-value of $4.88 \text{ W/(m}^2\text{K)}$, red clay brick walls had $2.48 \text{ W/(m}^2\text{K)}$, and insulated red clay brick walls had $1.31 \text{ W/(m}^2\text{K)}$.

(8) Sambucci & Valente [39] investigated the effect of fractal cavities or holes in cement bricks and found that **complex hole shapes**, or **geometric irregularity**, are a key feature in thermal flow attenuation, observing an increase of over 30% in thermal resistance for the best-performing brick compared to conventional designs.

(9) Al-Tamimi *et al.* [83] studied the effects of hole geometry on heat transfer in concrete masonry bricks. Results showed that **increasing the hollow ratio** (area of holes divided by the cross-sectional area of the brick) significantly reduced heat transfer. For example, a 51% hollow ratio could reduce the average inner surface temperature by $7.18 \text{ }^\circ\text{C}$, which is a 20.3% reduction compared to solid bricks. They also found that rectangular hole shapes were more thermally efficient than circular ones (with a difference of $0.29 \text{ }^\circ\text{C}$), and that **staggered hole arrangements** generally had advantages (with reductions of $0.22 \text{ }^\circ\text{C}$ and $0.31 \text{ }^\circ\text{C}$) over non-staggered patterns due to an increased heat path length. They also discuss that the **presence of barriers** within the bricks, and decreasing the **number of webs**, can decrease heat flux.

(10) Nemova *et al.* [70] studied the thermal performance of several 3DPC wall geometries which incorporated different air cavity shapes and numbers of rows, observing that the **heat flux through solids is severely higher (up to two times) than the heat flux through air**. Additionally, they concluded that convection also influences heat flux distribution on surfaces.

(11) De Rubeis *et al.* [11] experimentally investigated the thermal performance of three uninsulated 3DP blocks made of PLA with differing internal geometries: (1) hexagonal air cavities with no horizontal partitions, tested in both vertical (a) and horizontal (b) orientations; (2) hexagonal air cavities with three horizontal partitions; and (3) honeycomb structure characterized by three horizontal partitions and staggering along the vertical axis. Block 3 exhibited the best thermal performance, achieving a U-value of $1.08 \text{ W/(m}^2\text{K)}$, which was an 11.5% decrease compared to the U-value of block 1a, at $1.22 \text{ W/(m}^2\text{K)}$. The study attributes this to the insertion of **horizontal partitions**, the vertical translation of cells, and **increased geometric complexity**. Interestingly, block 1b (horizontal orientation) achieved a 7.4% decrease in U-value compared to block 1a, indicating an improved performance just by **changing cavity orientation from vertical to horizontal**. The thermal images also showed that block 3 demonstrated the most homogenous surface thermal distribution, in contrast to block 2 which showed significant vertical thermal stratification.

(12) Cuevas *et al.* [10] studied the thermal performance of seven 3DP wall elements for building envelopes, both numerically and experimentally. The study concluded that the primary factor governing thermal performance was the **number of closed chambers** (therefore leading to higher solid content), wherein increasing the number led to lower heat transfer values due to additional surface thermal

resistances between the material and the air. With a material conductivity of 0.46 W/(mK), variant E was shown to have the lowest U-value, at 1.27 W/(m²K). However, the study noted that uninsulated components were not suitable for extreme external temperatures of -16 °C due to significantly low resulting internal surface temperatures.

(13) Marais *et al.* [90] analyzed 3DP concrete wall structures with parallel cavities using lightweight foam concrete and high-performance concrete. For lightweight foam concrete, they found that a solid wall performed better thermally than a 3DP wall with large, wide cavities, but introducing **more cavities with smaller widths** enables significantly improved performance. At the same outer dimensions, a wall with four 20 mm wide cavities showed a lower internal temperature (21.15 °C) than the solid wall (21.40 °C), while the wall with five cavities of 9 mm width exhibited the best insulation properties, with an internal temperature of 20.98 °C. Further, the study noted that neglecting cavity radiation and convection might significantly underestimate heat transfer through a cavity wall system, by as much as 6.6%. Finally, the authors concluded that thermal performance and optimal wall geometry were **material dependent**. Materials with higher thermal conductivity (such as the high-performance concrete) tended to perform better as 3DP cavity walls, while those with lower conductivity (e.g. the lightweight foam concrete) tended to perform better as solid walls, but carefully designing geometry allows cavity walls to surpass the latter's performance.

(14) Chamatete and Yalçinkaya [11] evaluated three 3DPC wall lattice geometries: truss-type, zigzag-type, and cob-like weave, showing how **void areas** significantly influence heat transfer under stagnant air conditions. They discuss that since air conductivity increases with larger air void sizes (mainly due to convection currents), smaller voids correlate with improved insulative properties. Using a material with 0.979 W/(mK) conductivity, truss-type walls, with the largest void percentage (58.4%) exhibited the poorest performance (3.485 W/(m²K)), while cob-like walls showed superior resistance due to smaller void sizes and percentage (53.2%), resulting to a U-value of 2.77 W/(m²K). They concluded that increasing the filament width resulted in a decrease in U-values across all wall types, resulting to an insulative effect due to increased concrete area, and therefore, reduced void percentage.

Role of layer thickness on level of complexity

It can be seen from Table 3 that the nozzle diameter, and consequently the layer thickness (the width of the print extrusion), are parameters that can dictate the level of intricacy and complexity achievable in 3DP geometries. This complexity, in turn, can influence thermal performance. For instance, in Curth's study [14], the 4 mm layer thickness used for the 15 cm brick allowed for a much more complex infill, with more voids and intermediate rows, compared to the 3 cm layer thickness used for the 50 cm wall. Briels *et al.* [9] used a 12 mm layer thickness, achieving up to four layers of cells in a 30 cm deep wall. Suntharalingam *et al.* [71], on the other hand, achieved only up to two rows of infill geometry in a 20 cm deep wall, using a 25 mm layer thickness. It is important to note that the mortar material can influence the feasible nozzle size, and in turn, the layer thickness. Curth *et al.* [14] mention that a larger nozzle was needed to pump the soil mix for the wall, compared to the clay brick, while the cement mortar with rubber by Sambucci and Valente [39] needed to use a 10 mm circular nozzle due to the mortar's rheological properties.

However, the higher level of intricacy allowed by smaller layer thicknesses can also introduce trade-offs. In the study of de Rubeis *et al.* [88], for example, it was found that increasing the internal complexity from a multi-row design to a honeycomb structure significantly increased the printing time and print volume. The multi-row block consumed 438 g of PLA material and took 2 days, 1 h, 31 min to print, while the honeycomb block required 3 days, 7 h, 35 min to print, using 610 g. As such, it can be observed that thermal performance forms just one part of the objective, and the optimal balance among many factors

(e.g. cost, embodied carbon, and efficiency) must be considered for a more holistic assessment of the performance of 3D-printed elements.

Comparison of U-values with conventional wall references and standards

When comparing the U-values of the 3D-printed geometries analyzed in this study to those of conventional wall constructions, several noteworthy observations emerge. Overall, the U-values of the 3D-printed geometries are lower than those of standard 20 cm concrete brick walls (4.88 W/(m²K)), red clay brick walls (2.48 W/(m²K)), and even insulated red clay brick walls (1.31 W/(m²K)), as reported by AlZahrani *et al.* [89]. Although a few 3DP geometries exceed the U-value of the insulated brick wall, the average U-value across all tested configurations is lower than that of conventional concrete brick walls.

It is important to emphasize, however, that these comparisons involve different wall thicknesses, ranging from 10 cm [88] to 50 cm [14], the latter being significantly larger than conventional wall thicknesses. At the same time, the materials used in these studies vary and thus possess different thermal conductivities. Nonetheless, this comparison can offer a benchmark of where the performance and progress of 3D-printed wall geometry research currently stands.

One insight is that most of these 3D-printed geometries do not meet European U-value standards for external walls. For instance, the maximum U-values permitted by building regulations are 0.30 W/(m²K) in France and England, 0.28 W/(m²K) in Germany, 0.37–0.8 W/(m²K) in Spain, and 0.204 W/(m²K) in Finland [65]. Despite this, however, geometric optimization remains essential as it can reduce reliance on additional measures, such as insulation, and support the development of more environmentally-friendly solutions. Additionally, improved thermal efficiency without the use of insulation can benefit interior walls, which have less stringent requirements, allowing for more cost-effective building solutions.

2.6.3. SYNTHESIS: IMPROVING THERMAL PERFORMANCE THROUGH TOPOLOGY

Based on the reviewed geometries and results above, a tabulated summary of topological design principles that influence thermal performance was created in Table 4 below. The literature review suggests that the improved thermal performance of these designs is related to the following key factors:

- (1) **Thermal mass.** Having a denser infill geometry, especially on the interior side, is seen to improve the thermal performance of a 3D-printed component in the appropriate contexts. Having a higher thermal mass dampens indoor air temperature fluctuations and prevents extreme indoor temperatures. This was demonstrated by Curth *et al.* [14] who discussed that adding more material into the brick's infill can increase its storage capacity and number of air pockets, thereby improving its time constant or its ability to dampen and time-shift indoor temperatures. Further, they found that bricks with a gradient in their void structure had higher time constant values, with smaller air pockets on the interior side (for higher internal heat capacity where it is more needed) and larger voids on the outer side (to reduce the needed material and therefore, embodied carbon). In the Tecla [86] and Digital Adobe projects [84], thermal mass was employed through the "ribbing" of the sinusoidal infill and adding earth to the infill cells, respectively.

Related to mass, the U-values of walls also generally decreased with increased wall thickness, regardless of cross-sectional configuration, as demonstrated by comparing the geometries within the study of Suntharalingam *et al.* [71]. Several of the built 3DP projects also possessed high wall thicknesses, averaging 45 cm and reaching up to 70 cm thick.

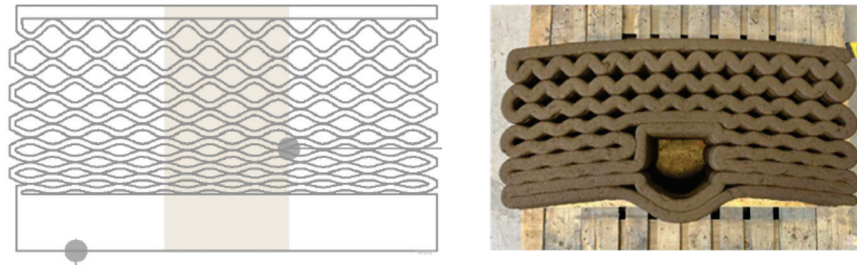


Figure 9 - Thermal mass implementation on the interior side of the wall [14].

- (2) **Air voids.** The studies show that the impact of air void percentage, size, number, shape, and distribution on 3DP thermal performance is a complex interplay, dependent on how these voids influence conduction, convection, and radiation.

Void percentage. According to Briels *et al.* [9], a reduction of the relative density, i.e. higher void percentage or porosity, decreases the equivalent thermal conductivity of the cellular solid, owing to the lower conductivity of the gas compared to the solid. This phenomenon can be observed in the study by Al-Tamimi *et al.* [83], which shows that the bricks with the highest void percentage exhibited the lowest interior temperatures. However, this contradicts the conclusions of Cuevas *et al.* [10], Marais *et al.* [90], and Chamatete and Yalçinkaya [11], who noted that a reduced void percentage due to having a higher solid area (which can allow having more interior partitions and smaller cavity sizes in the geometry) leads to improved performance. Chamatete and Yalçinkaya [11] discuss that this is because the thermal conductivity of stagnant air is proportional to the thickness of the air layer, and so higher void percentages (which are usually correlated with larger void sizes) lead to poorer insulative performance. This contradiction among studies may be attributed to differences in the dominant mode of heat transfer through the geometries: if most of the heat transfer occurs through the air voids (i.e. air conductivity is higher than the solid's), reducing void percentage can provide an insulative effect [11]; otherwise, if the solid facilitates most of the heat transfer, then increasing void percentage or porosity can improve performance [9]. Moreover, in studies which considered different geometries with a constant void percentage [39, 89], it can be seen that other factors like void size, shape, and distribution play a significant role in determining thermal performance, showing that void percentage is not the sole determining factor.

Void size and number. Literature suggests that in stagnant air conditions, buoyancy-driven natural convection and radiation can be decreased by reducing the cavity size or optimizing the aspect ratio, or the ratio of the cell height to the cell diameter or size [5] [88]. The optimization of Briels *et al.* [9] indicated a favorable aspect ratio of greater than 2 for optimized thermal performance. Dielemans *et al.* [91] pointed out that a decrease in cell size from 199 to 65 mm can improve the U-value by up to 40%, even with a decreased air-to-solid ratio. Al-Tamimi *et al.* [6] also discuss that the insulative properties of cavities deteriorate once their width exceeds 40 mm. It was observed that subdividing large cavities into smaller ones reduces heat flux. The number of independent chambers or cells can greatly influence the improvement of the U-value, with more closed spaces resulting to lower U-values. This is attributed to an increased surface resistance to heat transfer between the air and the printed material [10]. This effect can be seen in the studies of Cuevas *et al.* [10] (shown in Figure 10), Marais *et al.* [90] (five cavities), Curth *et al.* [14], de Rubeis *et al.* [88] (square and hexagon), Suntharalingam *et al.* [71] (double-row triangle and sinusoid), AlZahrani *et al.* [89] (square and hexagon), and Nemova *et al.* [70] (triple-

row triangular) wherein the most subdivided geometries with smaller voids consistently obtained the lowest U-values, even sometimes at equal void percentages.

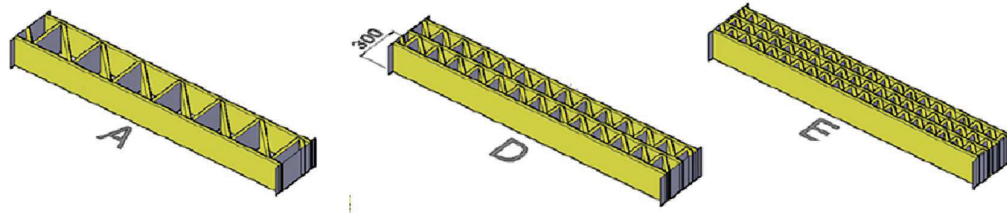


Figure 10 – Variant E, with the most void subdivisions at smaller sizes, possessed a lower U-value ($1.27 \text{ W}/(\text{m}^2\text{K})$) than variant D ($1.54 \text{ W}/(\text{m}^2\text{K})$) and variant A ($2.17 \text{ W}/(\text{m}^2\text{K})$) at the same wall thickness [10].

However, certain studies demonstrate some thresholds to this subdivision. The study of Briels found that for their 3DPC wall, reducing the cell diameter below 70 mm did not provide further improvement to thermal performance. Additionally, their analysis found that below a 10 mm diameter of air-filled cells, free convection already becomes irrelevant. This suggests that further subdivision beyond this point may lead to diminishing returns, as convection is already significantly reduced. It is important to note, however, that these thresholds may be specific to the materials and geometric configurations used in that study. Further research is necessary to determine whether similar limits apply to other materials and design strategies.

Void shape. Piccioni *et al.* [92] noted that elongated cells with small dimensions in the direction of heat transfer could minimize convection. Similarly, Li *et al.* [12] discuss that voids should run perpendicular to heat flow to prevent creating direct channels for heat, and that introducing several parallel cavities can transform convection-dominated heat transfer into conduction. This increases radiation resistance, lowers the heat transfer rate, and therefore thermal transmittance. This approach can be seen especially in the studies [14, 22, 83], with the latter featuring a quadruple air void perpendicular to the heat flow direction, resulting in the lowest interior temperature in the study. This is supported by Marais *et al.* [90] who discussed that for the same cavity to footprint ratio, more and narrower cavities improve thermal insulation. Finally, the analysis of the tetrakaidecahedron geometry of Briels *et al.* [9] shown in Figure 11 shows that vertically elongated cells can also minimize thermal convection.

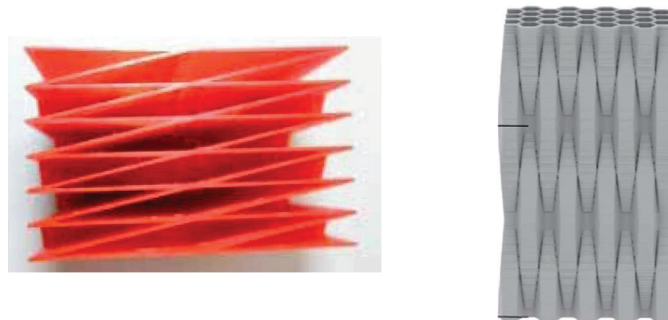


Figure 11 - Left: Horizontally elongated cells [22]. Right: Vertically elongated enclosed cells [9].

Closed voids. According to Briels *et al.* [9], convection can be reduced by encapsulating air in cells, as it limits buoyancy-driven natural convection, with smaller volume sizes having reduced natural convection. Specifically, closed cellular structures with a low surface area to volume ratio are also seen to have improved thermal performance because it decreases the average thermal conductivity of the cellular solid [9]. Enclosing air, such as by using horizontal partitions, especially those staggered, can mitigate convective heat transfer, increase the geometric complexity, and attenuate thermal conduction [1], as seen in Figure 12.

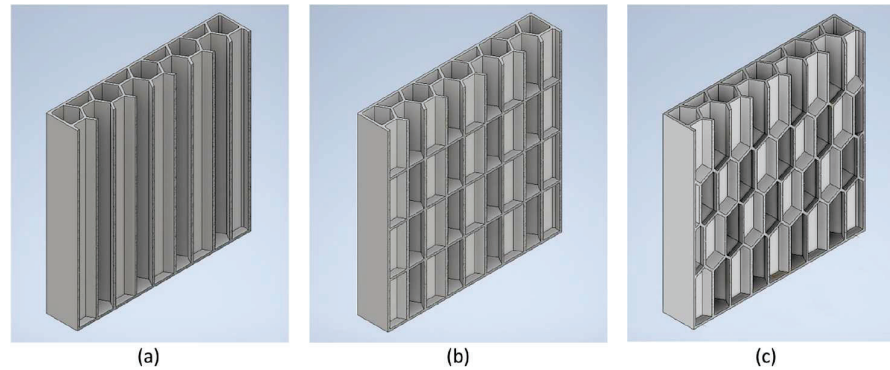


Figure 12 - Horizontally closed-cell structures can improve thermal performance compared to open-cell structures [1].

- (3) **Thermal bridging and thermal lag.** According to Cuevas *et al.* [10], walls with perpendicular webbing connections between interior and exterior sides exhibit higher heat flux values, thereby increasing heat loss, while those with web connections at smaller angles to the wall surface had lower heat flux values, leading to improved thermal performance. This is why longer heat paths, like those of the diamond configuration of AlZahrani *et al.* [89], or the staggered and complex layout of the fractal hole brick of Sambucci and Valente [39], exhibited the lowest U-values in their respective studies. Their lengthened paths for the heat to cross through the wall resulted in an increased resistance to heat transfer. Conversely, shorter, direct paths like in the rectangular designs of AlZahrani *et al.* [89] (shown in Figure 13) and de Rubeis *et al.* [88], or the square topology of Nemova *et al.* [70], resulted in higher U-values.

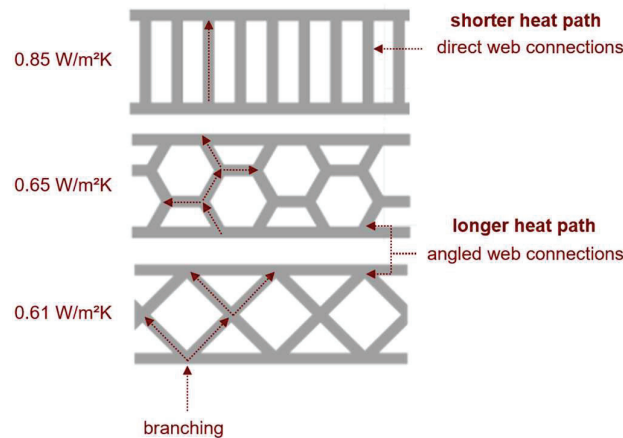


Figure 13 - The diamond geometry outperformed the other geometries due to longer heat paths from exterior to interior [89].

Branching patterns in hexagonal and diamond shapes [89] and the intricate complex geometry of Curth *et al.* [14], which provide more ways for energy to travel, also reduced heat transfer and lowered U-values. The TerraPerforma [85] project used several degrees of bifurcations to increase the number of ways for the energy to travel and disperse within the wall thickness, as shown in Figure 14. These complex shapes, according to Mihalache *et al.* [93], can also prevent overheating caused by radiation.

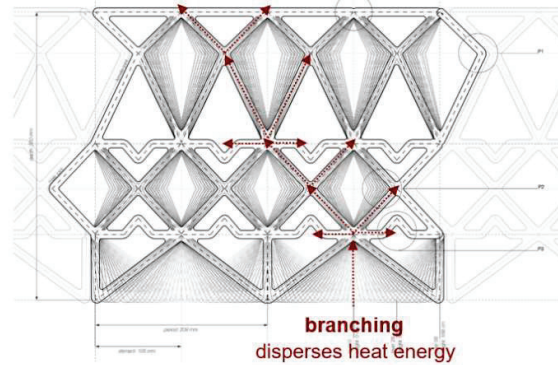


Figure 14 - The several degrees of bifurcations (branching) in the TerraPerforma project [85].

Related to thermal lag, preventing thermal bridging can involve having fewer web connections with smaller web thicknesses across the two sides of the component. These concepts are demonstrated in the best-performing geometries by Bruggi [61], which featured mechanical "cores" located at the center of the bricks, to which very thin and few webs are connected to prevent significant thermal bridging.

- (4) **Intermediate rows or barriers.** Multi-row configurations significantly and consistently reduced U-values compared to single-row designs. In the study of Suntharalingam *et al.* [71] for instance, double-row triangular and sinusoidal designs exhibited a 42.10% and 40.72% decrease, respectively, compared to single-row designs, in 200 mm thick walls (shown in Figure 15). Similarly, in 100 mm thick walls, double-rows reduced the U-value by 31% and 25% for triangular and sinusoidal configurations, respectively. Alkhalidi & Hatuqay [17] showed that double and triple-row wall geometries outperformed single-row geometries thermally, reducing U-values by 44% and 62%, respectively. Nemova *et al.* [70] also demonstrated that the triple-row triangular geometry possessed a lower U-value (0.86 W/(m²K)) than the double-row geometry (1.05 W/(m²K)). Sovetova & Calautit [2] report that a higher number of intermediate barriers correlates to reduced material conductivity, improving thermal efficiency. It was observed in the literature review that multilayered geometries (whether triangular or sinusoidal) are consistently the best performing in their respective studies.

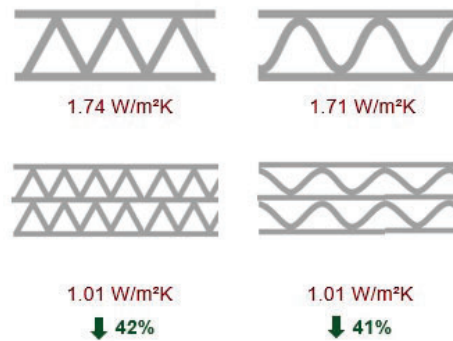


Figure 15 - Double-row triangular and sinusoidal geometries exhibited lower U-values than their single-row counterparts [71].

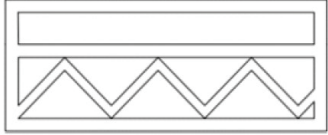
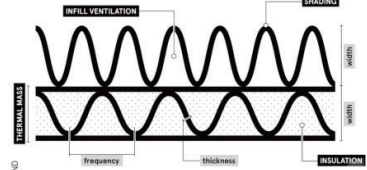
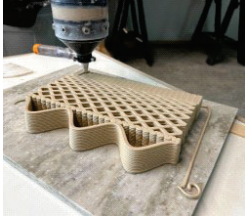
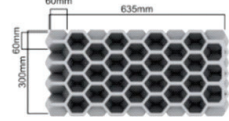
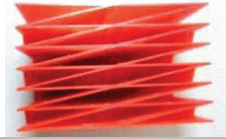
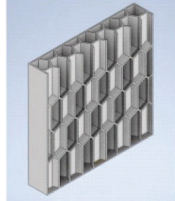
- (5) **Exterior shape.** The sinusoidal geometries of several of the constructed case studies (e.g. Digital Adobe [84], TerraPerforma [85]) result to exterior waves or bumps on the wall, acting to increase self-shading during summer, and maximize solar radiation during winter. These are shown in Figure 16. Although the effects of most of these interventions have not been explicitly quantified, similar design decisions can be made to positively impact envelope designs, whether aesthetically or functionally.

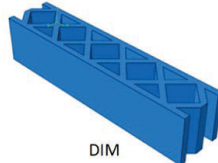
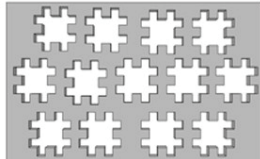
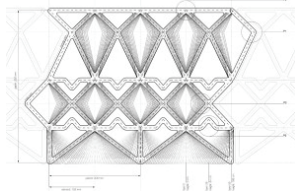
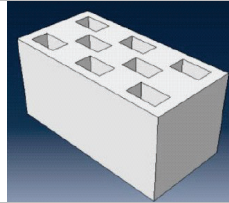
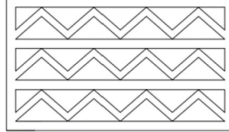
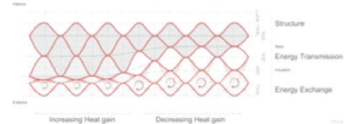


Figure 16 - The undulations of exterior wall surfaces can positively impact thermal performance. Left: Digital Adobe [84], right: TerraPerforma [85].

While these factors all contribute to a 3DP envelope's thermal performance, their combined effects determine overall efficiency. Overall, it is clear that topology can greatly impact the thermal behavior of structures [6]. While additional insulation might still be necessary to meet higher energy efficiency standards, it is important that the topology of 3DP components be optimized as much as possible to reduce dependence on additional active or passive measures, which could increase carbon emissions.

Table 4 - Summary of topology design concepts for thermal performance.

Topology Concept		Effect	Examples	
Thermal mass	More material/more dense geometry at interior side	dampen indoor air temperature fluctuations and prevent extreme indoor temperatures		[14]
	High wall thickness			
	Natural insulation at interior side			
	High void percentage / low relative density	high thermal inertia, enhances thermal resistivity		[70]
	closed ventilation chambers on the exterior	Air acts as an insulator in the static state in closed cells; however, in the dynamic state, it can accelerate heat transfer due to convection		[31]
Air pockets/cavities	Many, small infill cavity structures to reduce heat exchange	By decreasing the cell size, the buoyance-driven natural convection can be reduced		[14]
	Closed cellular structures with low surface area (low A/V ratio)	decreases the mean thermal conductivity of the cellular solid		[9]
	Parallel elongated cavities in all directions except the direction of heat transfer (voids should be perpendicular to heat transfer)	minimise convective heat transfer		[22]
	Staggered horizontal partitions	mitigates convection effects, increases the geometric complexity of the block, attenuating thermal conduction		[1]

Topology Concept		Effect	Examples	
Thermal bridging and thermal lag	Longer heat conduction path (webs at an angle to the wall surface)	lengthen the path that heat must follow to cross the wall		[89]
	Complex geometry of shapes	thermal attenuation: thermal trajectory is maximized and therefore the convection heat transfer is reduced	 <i>Fractal holes brick (FB)</i>	[39]
	Branching patterns	more ways for the energy to travel and disperse within the wall thickness		[85]
	Rectangular holes/voids instead of circular ones	discontinuity in the path of heat flow, length of the path becomes longer		[83]
	Staggered patterns	lengthen the path that heat must follow to cross the wall		
	Fewer web connections, mechanical "core" at the center Smaller web thicknesses	decreases thermal bridging and heat transfer		[61]
Multiple rows/layers		reduction in material conductivities		[70]
Exterior shape	Bumps/waves on surface	self-shading during summer; maximum radiation during winter		[84]

2.6.4. METHODS FOR MEASURING THE THERMAL PERFORMANCE OF 3DP COMPONENTS

Based on literature, measuring the thermal performance of a 3DP component can be carried out either by numerical simulations, experimental tests, or both. Table 5 below shows a summary of research articles which employed numerical simulations for testing, while Table 6 summarizes those that tested out physical samples experimentally.

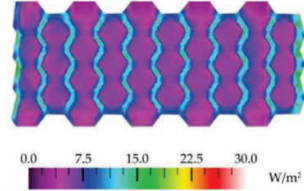
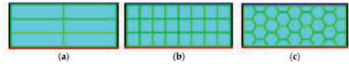
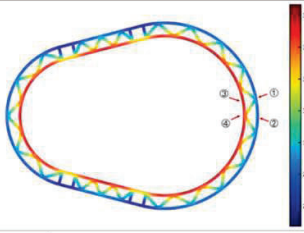
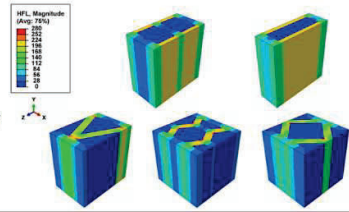
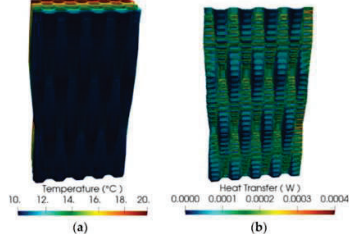
Table 5 shows a summary of research articles which employed numerical simulations. The studied articles made use of several numerical simulation software for assessing the thermal performance of both wall and brick 3D-printed components. The most used of these was ABAQUS Finite Element Model, used by AlZahrani *et al.* [89], Suntharalingam *et al.* [71], and Al-Tamimi *et al.* [83]. Aside from being used for engineering simulations on acoustics and electrochemistry, ABAQUS is used widely in different industries for three-dimensional (3D) heat transfer analysis, capable of modeling conduction, convection, and radiation [94]. Another commonly used software was LBNL Therm Numerical Heat Transfer Model used by Briels *et al.* [9] and de Rubeis *et al.* [88], which uses two-dimensional (2D) conduction and radiation heat transfer analysis based on the finite-element method [95].

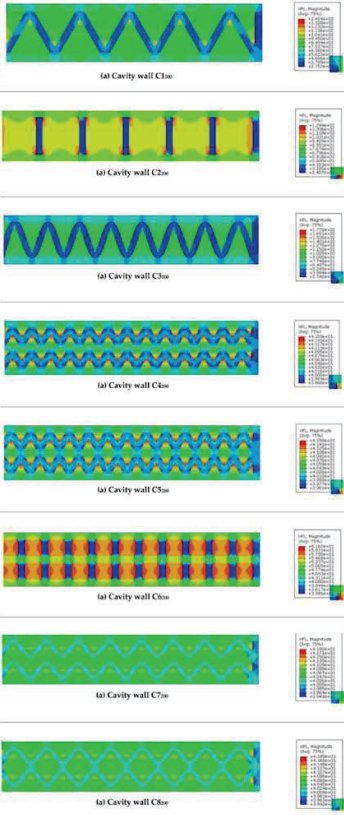
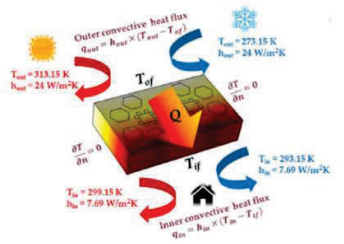
The inputs for these simulations typically include the component's geometry, including the shapes of internal cavities or voids. In addition, material properties (including those of air) like thermal conductivity, density, specific heat, and emissivity are needed. As can be seen in the table, all the studies required the input of some form of boundary conditions, such as indoor and outdoor temperatures, and convective and radiative heat transfer coefficients for surfaces. On the other hand, the outputs of these simulations are most commonly U-values, but other studies outputted temperatures at specific points and thermal resistance. All these tools visually represent heat flux distributions and temperature fields usually with color gradients, to offer insight into pathways of heat transfer and thermal bridging.

It is important to note that these simulation methods have limitations. For instance, Briels *et al.* [9] discuss that while 2D simulations require less computational demand and can be embedded directly into design workflows, they evaluate only representative cross-sections and therefore simplify the complexity of 3D heat flow. This can potentially neglect vertical thermal behavior and cause inaccuracies in the results. In contrast, 3D simulations can provide a more comprehensive analysis of the entire element and also assess localized thermal behavior, but demand significantly higher computational power and time.

Some of the simulations also did not account for all three heat transfer mechanisms, either due to software limitations or the focus of the study's scope. For instance, AlZahrani *et al.* [89] considered solely heat conduction in their analysis, while Nemova *et al.* [70] did not include radiative heat transfer. On the other hand, Briels *et al.* [9] simplified how convection and radiation are modeled within internal air cavities by assigning effective thermal conductivity coefficients rather than explicitly solving for these phenomena.

Table 5 - Numerical simulations used by research articles to measure thermal performance.

Study	Numerical simulation software	2D/3D	Material	Boundary conditions	Mesh size	Output	Images
Briels et al. 2022 [9]	Heat Flux using LBNL THERM	2D	Concrete	1. Temperature on both sides; convection and radiation components on all surfaces (ISO 6946:2017-06) [15]	not specified	U-value	
de Rubeis et al. 2022 [88]	Numerical Heat transfer modeling using LBNL THERM	2D	PLA	External surface: 1. temperature: 25 °C 2. film coefficient: 25 W/(m²K) 3. thermal resistance: 0.04 (m²K)/W (EN ISO 6946) Internal surface: 1. temperature: 40 °C 2. film coefficient: 7.69 W/(m²K) 3. thermal resistance: 0.13 (m²K)/W (EN ISO 6946) [15]	automatic ly generated	U-value	
Li et al. [12]	OpenPNM	2D	Concrete	1. heat transfer coefficients: 7.69 W/(m²K) on both sides 2. 2-h heat transfer simulation 3. boundary conditions: ambient temperature data and 23.8 °C as the initial temperature	30 mm and 6 mm	Temperature (°C)	
AlZahrani et al. 2022 [89]	ABAQUS Finite Element Model	3D	Concrete	1. same boundary conditions as the hot guarded-plate method by Dickinson and Van Dusen 2. interior temperature: 21 °C 3. exterior temperature: 30 °C (daily mean temperature of Makkah, Saudi Arabia)	0.0075 m	Thermal conductivity	
Briels et al. 2022 [9]	Computer Code S1: FCMLab (Finite Cell Method) https://gitlab.lrz.de/cie_sam_public/fcm_lab	3D	Concrete	Temperature on both sides; convection and radiation components on all surfaces (ISO 6946:2017-06) [15]	not specified	U-Value	

Study	Numerical simulation software	2D/3D	Material	Boundary conditions	Mesh size	Output	Images
Suntharalingam et al. 2021 [71]	ABAQUS Finite Element Model (3D heat transfer analysis)	3D	Concrete	External surface: 1. temperature: 0 °C 2. convective surface heat-transfer coefficient: 25 W/(m²K) (EN ISO 6946) [15] 3. surface film coefficient: 25 W/(m²K), sink temperature: 0 °C Internal surface: 1. temperature: 40 °C 2. convective surface heat-transfer coefficient: 7.69 W/(m²K) (EN ISO 6946) 3. surface film coefficient: 7.69 W/(m²K), sink temperature: 40 °C Heat-transfer elements (DC3D8 elements) were used Air thermal transmittance: 0.18 (m²K)/W	Global seeding: 10 mm Edge seeding: 2 mm	U-value	
Sambucci and Valente, 2021 [39]	Heat Transfer in Solids Module of COMSOL Multiphysics 5.4	not specified	Cement with Rubber	1. SUMMER outdoor temperature: 40°C indoor temperature: 26°C 2. WINTER outdoor temperature: 0°C indoor temperature: 20°C 3. outdoor heat flux coefficient: 24 W/(m²K) 4. indoor heat flux coefficient: 7.69 W/(m²K) (ISO 6946) [15] 5. average wind velocity: 3.6 m/s 6. clear sky normal irradiance: 236 W/m² (summer); 64 W/m² (winter)	maximum 20 mm	Thermal resistance	

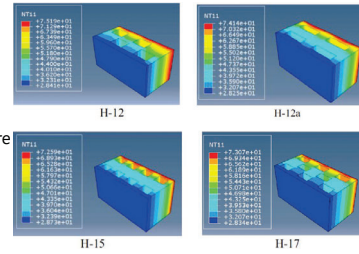
Study	Numerical simulation software	2D/3D	Material	Boundary conditions	Mesh size	Output	Images
Al-Tamimi, 2017 [83]	ABAQUS	3D	Concrete	EN ISO 6946 [15] 1. Air outer temperature = 46 °C 2. For the top, bottom and side surfaces of the brick, symmetrical BCs were assumed and, hence, no heat loss occurred. 3. For convection, inner ambient air temperature: 25 °C 4. average solar radiation for outside surfaces: 746 W/m ²	5 mm	Temperature	
Nemova, 2022 [70]	ANSYS CFX	3D	Concrete	1. heat transfer coefficient values: Churchill and Chu approximation 2. convective temperature outside: -24°C 3. convective temperature inside: +22 °C	not specified	U-value	

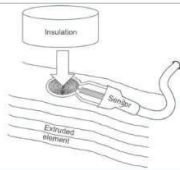
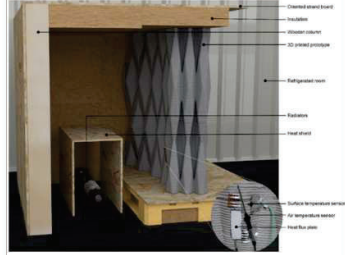
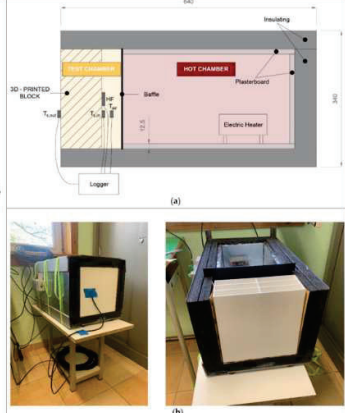
Table 6 gives a summary of the experimental tests carried out in the reviewed studies. The majority of the studies, such as the ones by Sarakinioti *et al.* [22], Briels *et al.* [9], de Rubeis *et al.* [88], and Alqahtani *et al.* [96], used a small hot box setup with the heat flux meter (HFM) method. These methods involve placing the 3D-printed sample between two chambers, which have different temperatures (one hot and one cold), thereby creating a temperature difference across the sample. Its main principle is to measure the heat flux passing through the specimen, in addition to air and surface temperatures on both sides [96]. As shown in the table, most of the tests were carried out based on the standards UNE-EN ISO 9869-1:2023 [97] for the heat flow method and UNE-EN ISO 8990:1997 [98] for the hot box.

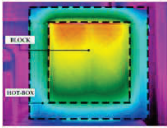
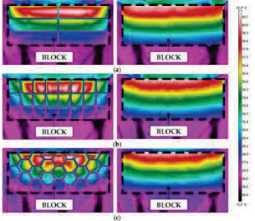
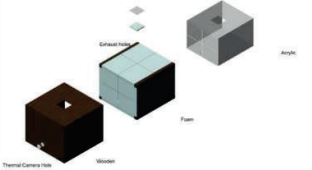
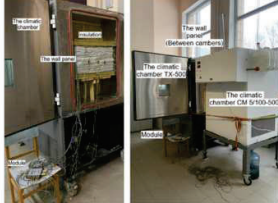
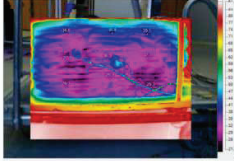
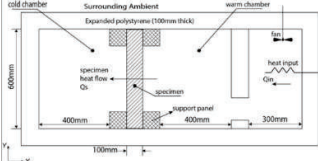
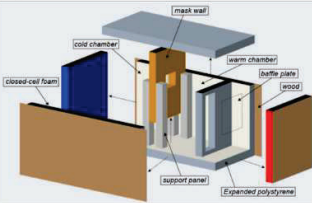
In addition, some studies [70, 88] used Infrared Thermography (IRT), which uses thermal cameras to visually represent heat flux distributions on the surface of the sample, which can help show the homogeneity of heat flow, or in other cases, thermal bridging.

The main outputs of the studied tests are commonly the U-value, temperature measurements, and thermal imagery. These experimental tests are important as they can characterize the actual thermal performance of the samples, versus analytical or numerical simulation models. By comparing experimental results with simulation outputs, the reliability of numerical models can be assessed.

However, the studies discuss a number of limitations of these experiments. For instance, inaccuracies to measurements may occur due to unintended heat loss through chamber walls [96], malfunctions of sensors, or external temperature fluctuations [9]. In addition, sometimes there may be discrepancies between the designed geometries for the simulations and the “as-built” samples, due to printing inaccuracies, cracks, or imperfections [9]. In turn, these can lead to deviations between theoretical and experimental results.

Table 6 - Experimental tests used by research articles to measure thermal performance.

Study	Experimental method	Standard used	Material & sample size	Equipment/devices	Boundary conditions	Output	Images
Sarakinioti et al. 2018 [22]	Hot Box heat flux test	not specified	PETG (Thermoplastic polyester) 200 mm x 200 mm	1 cu.m. polystyrene box lamp thermocouples heat flux plate (Hukseflux HFP01)	Only the long-term average results were used once a steady-state situation had been reached	Thermal conductivity	N/A
Briels et al. 2022 [9]	Hot disc method (ISO 22007-2:2015-12) [118]		Concrete		ambient temperature of 19 ± 2 °C	Thermal conductivity	
	Heat flow meter method Calibrated and guarded hot box	ISO 9869-1:2014 for the HFM, complemented with ISO 8990:1994 for the hot box [97] [98]	Concrete 1200 mm x 1040 mm ht. x 800 mm thk.	two radiators (2 x 250 W) attached to a proportional-integral-derivative (PID) controller digital heat flow plate (Ahlborn FQAD117T) integrated NTC (negative temperature coefficient thermistor) temperature sensor	outside air temperature: 13 °C to 16 °C indoor air temperature: 23 °C to 25 °C	U-value	
de Rubeis et al. 2022 [88]	Hot Box: Heat Flux Meter (HFM)	EN ISO 9869-1:2014 [97]	PLA 250 mm x 250 mm x 100 mm thk.	heat flux sensor, temperature probes, data logger, electric heater	external temperature: 25 °C internal temperature: 52 °C *temperature difference of at least 15–20 °C Ten-hour measurements with an acquisition time of 10 min were carried out for each block	Thermal conductivity, resistance and U-value	

Study	Experimental method	Standard used	Material & sample size	Equipment/devices	Boundary conditions	Output	Images
de Rubeis et al. 2022 [88]	Infrared Thermography (IRT)	not specified	PLA 250 mm x 250 mm x 100 mm thk.	Thermal camera		thermal imagery	 
Dubor 2017 [52]	Thermal simulation machine	none specified	Clay	Thermal simulation machine	240 minute-period	Humidity Temperature	 
Nemova et al., 2022 [70]	Climatic chamber	not specified	Concrete 390 mm x 680 mm x 310 mm.	Climatic chamber 1, 2; flux density and temperature meter	Climatic chamber No. 1: -24 °C Climatic chamber No. 2: +22 °C values recorded every 15 min.	Temperature and heat flow	
	Thermal Imaging			Fluke TIS60 + Thermal Imager	frequency of filming is 20 min.	thermal imagery	
Alqahtani et al., 2023 [96]	Hot box calorimeter: temperature-hot chamber approach	EN ISO 8990 (for hot box) and ISO 9869 (for sensors and instruments) [97] [98]	PLA 200 mm x 200 mm	hot box, thermocouples, heat flux sensors, data loggers, and resistance temperature detectors	hot chamber temperature: 30°C cold chamber temperature: 5°C 72-hr runtime for each test	U-value	 

2.7. CONCLUSIONS

This state-of-the-art reviews several 3D-printed building envelope geometries from constructed projects and research articles, identifying design principles for improved thermal performance and the thermal concepts behind them. The review highlights that topological optimization in 3D-printed structures can indeed impact their thermal performance, with the key strategies identified as:

- (1) thermal mass distribution;
- (2) consideration of void percentage, size, number, shape, and distribution;
- (3) introducing thermal lag and preventing thermal bridging;
- (4) using multi-row or multi-layered configurations; and
- (5) manipulation of exterior shapes.

These topological design principles can act as the foundation for creating mono-material, energy-efficient, and thermally performative building envelopes using 3DP. While the body of research on 3DP topology and thermal performance is growing, certain research gaps and limitations still exist. Those identified are the following:

- There is a limited number of studies on 3DPE geometries and their thermal performance;
- The majority of studies focus on carrying out numerical simulations, instead of real-scale experimental evaluation and validation;
- Increasingly complex geometries could still be studied, which could improve thermal performance [14];

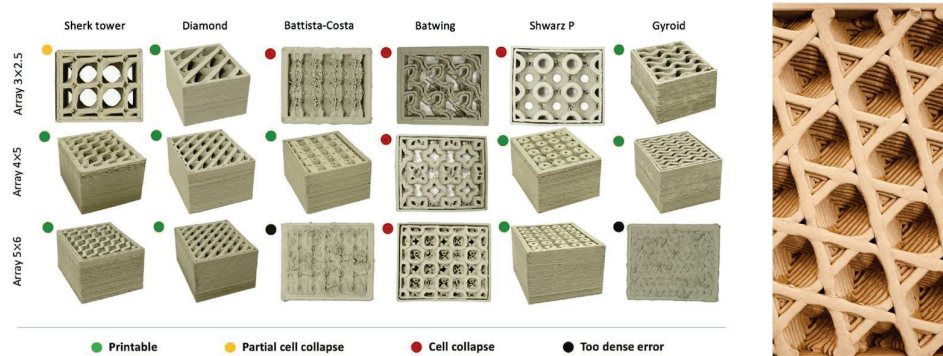


Figure 17 – Potential complex 3DP geometries for improved thermal performance. Left: Sangiorgio *et al.* [7], right: Curth *et al.* [14].

- The majority of studies conclude that the resulting U-values generally still do not comply with thermal performance standards, and components that do comply usually have insulation infill or have excessively high thicknesses;
- Joints or connections between components must be studied in order to prevent thermal bridging, and for expansion for printing long segments [14];
- There is a lack of studies on the coupling relationship between thermal and other performance aspects, such as structural [12], moisture [12], acoustics, fire, and sustainability.

Overall, while the review highlights the significant potential of 3DP topology optimization, it also emphasizes the need for further research and development in the area to address the identified research gaps and fully realize its potential.

3

CASE STUDY

3.1. METHODOLOGY

The study starts with a comprehensive state-of-the-art review, aiming to identify the primary factors that influence the thermal performance of 3D-printed wall geometries. These insights will then inform the conceptualization of the base geometries, which will be parameterized using the Rhino software and Grasshopper plugin, enabling the creation of various iterations through parametrization. These will then undergo numerical simulations, specifically using steady-state 3D heat transfer analysis. The primary goal of the simulations is to identify the geometries that achieve an optimal balance between thermal performance (represented in this study by the U-value) and other practical considerations, such as print path length, which is directly linked to factors such as print volume, printing time, cost, and embodied carbon. Following the simulations, selected geometries will proceed to scaled prototyping through 3D printing to gain initial insights into their buildability and printability. The research concludes by drawing conclusions based on the findings related to the mentioned factors, offering insights into the holistic performance of 3DPE wall components. This study employs an approach that integrates both qualitative analyses in the conceptualization of the geometries, and quantitative analyses in the numerical simulations stage. Figure 18 shows a summary of the methodology.

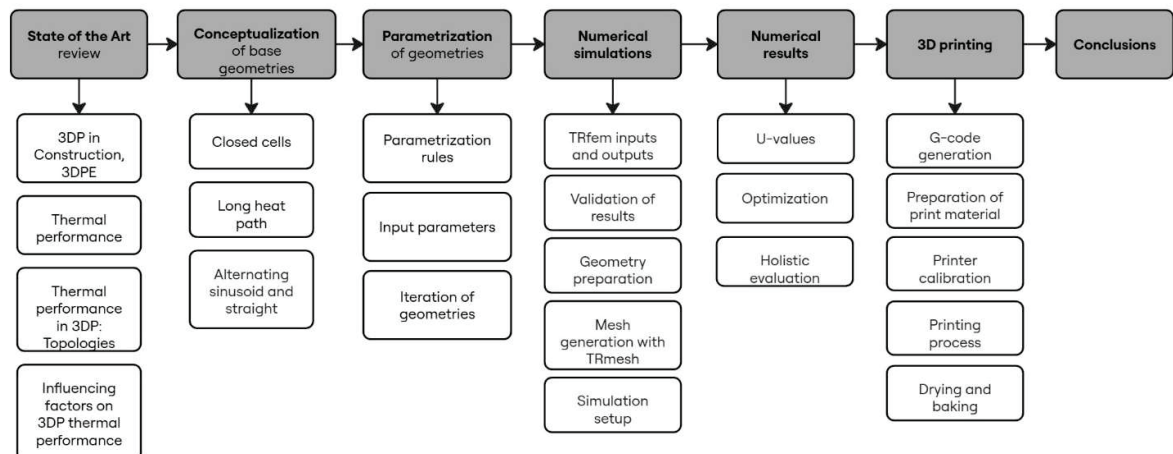
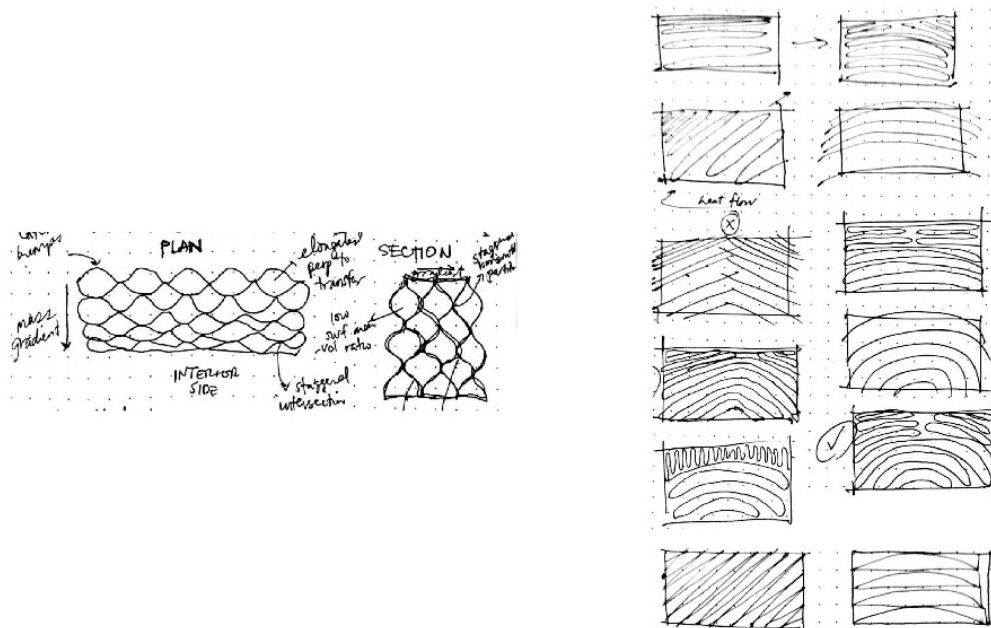


Figure 18 - Methodological flowchart. (Author's own).

3.2. CONCEPTUALIZATION OF BASE GEOMETRIES

Building on the findings from the state-of-the-art review, the next step involved the conceptualization of base geometries. The thermal concepts identified from the studied geometries were combined, reinterpreted, or innovated to inform the design of three novel base geometries for the wall components. Several designs were initially hand-drawn (Figure 19), directly applying the most salient principles and qualities derived from the literature review. These initial sketches were then refined and trimmed down based on a set of factors, including:

- the feasibility of the design given its complexity, based on a fixed layer thickness of 7 cm and a fixed wall thickness of 40 cm;
- initial projected evaluation of the printing path, printing time, volume, and overall buildability, which are critical for practical fabrication;
- the suitability of the geometry to be translated into a wall (meaning it could be extended indefinitely for onsite architectural application), or a brick (for off-site production);
- the absence of corners and the possibility of a continuous printing path to prevent print stopping, a common challenge in 3DP which results to longer printing time and increased material deposition;
- the possibility of being reduced/increased in complexity for the iteration process, enabling design flexibility.



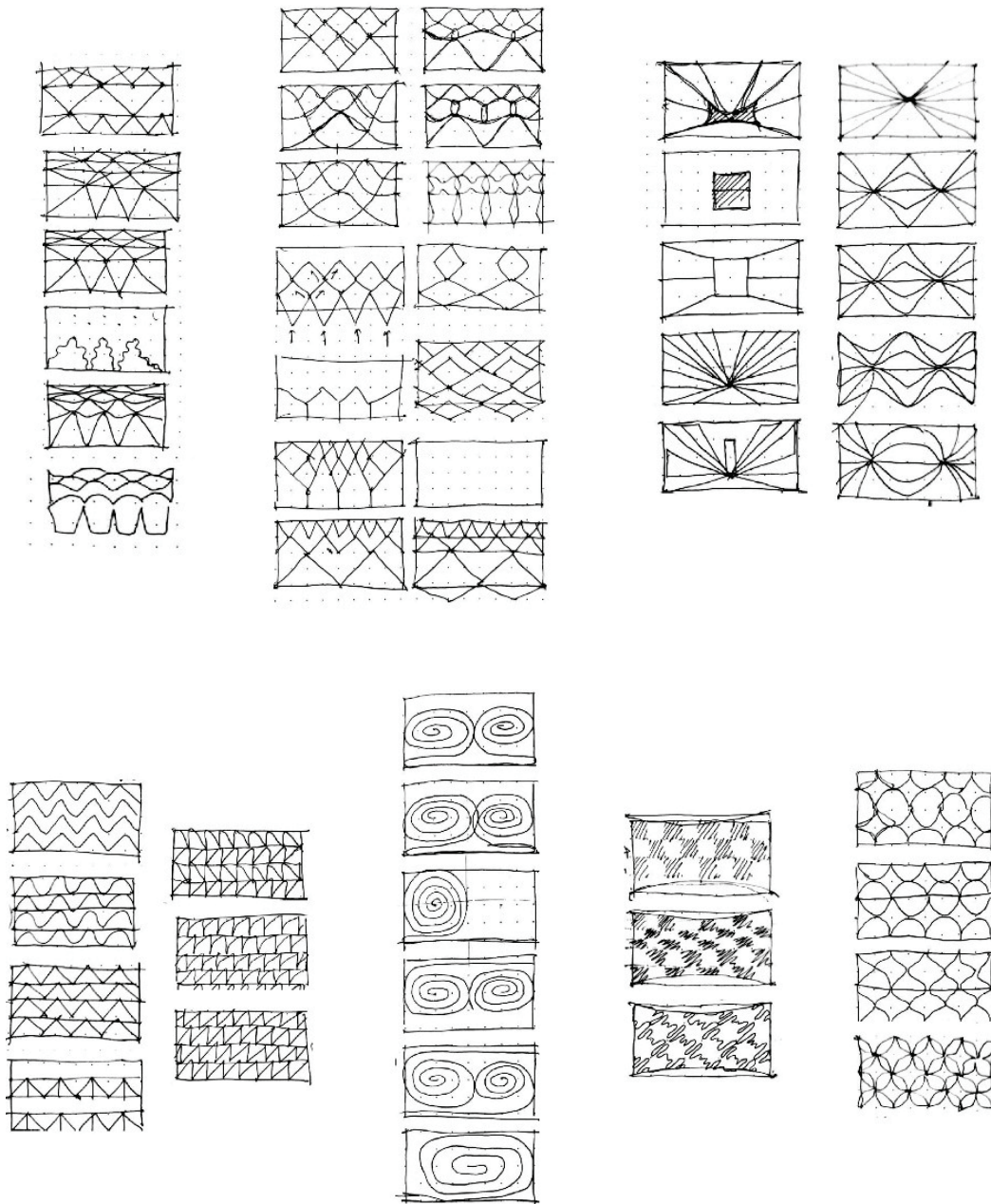


Figure 19 - Initial hand sketches of geometries. (Author's own).

Based on this evaluation, six designs were shortlisted:

- **Geometry A:** Closed cell structure, both horizontally and vertically, for improved insulation (Figure 20);

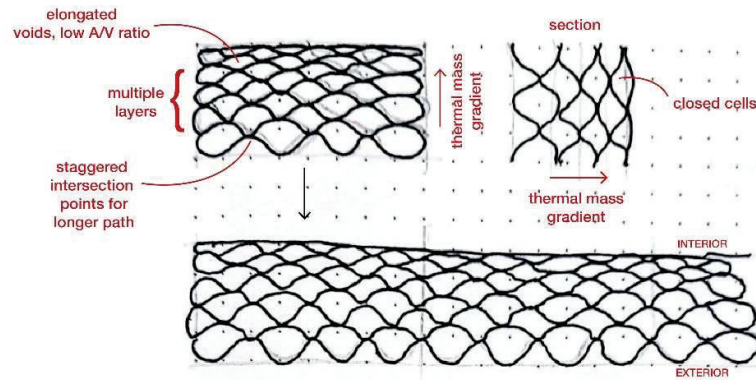


Figure 20 - Sketch of geometry A. (Author's own).

- **Geometry B:** Elongated heat path with no direct thermal bridges (Figure 21);

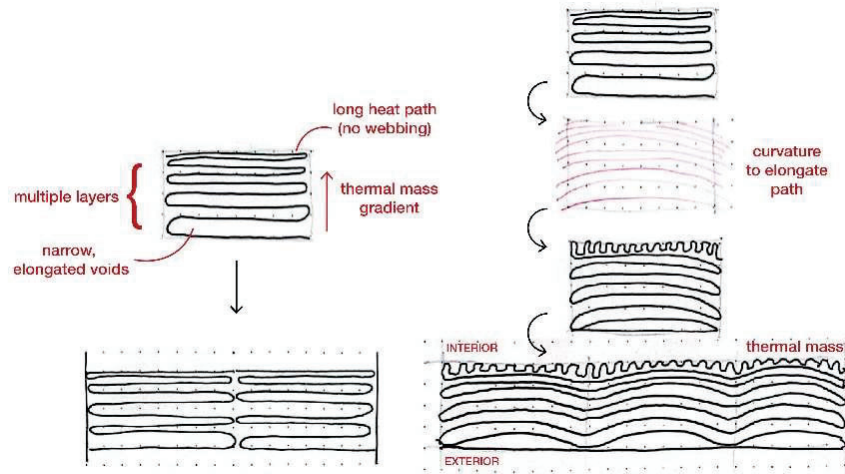


Figure 21 - Sketch of geometry B. (Author's own).

- **Geometry C:** Alternating sinusoid and straight layers for a subdivided void structure (Figure 22);

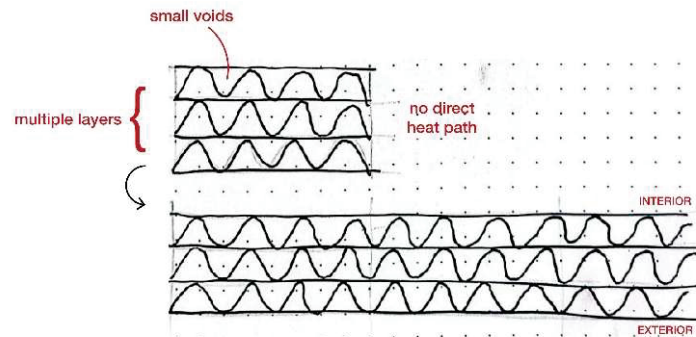


Figure 22 - Sketch of geometry C. (Author's own).

- **Geometry D:** Branching pattern for a dispersed heat flow (Figure 23);

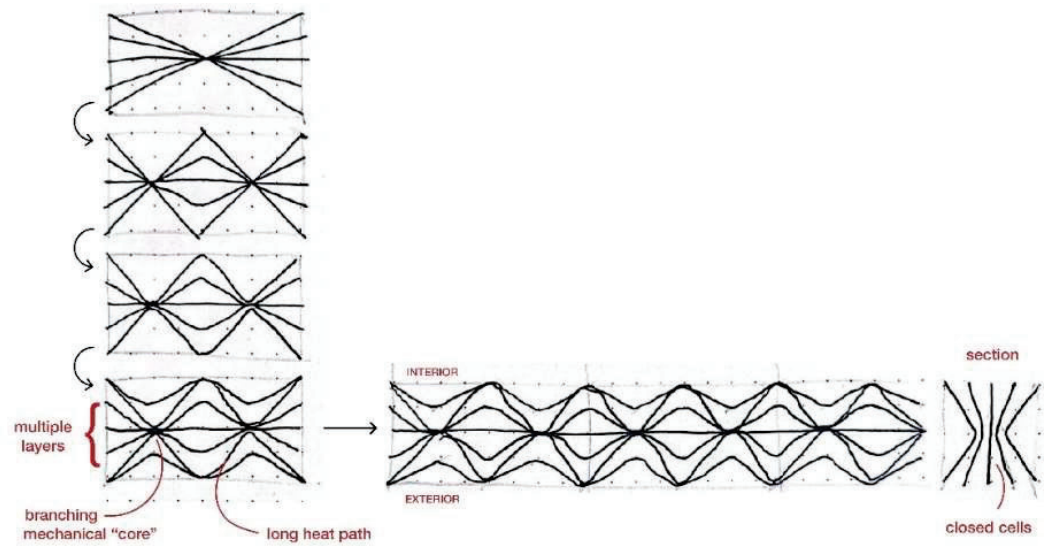


Figure 23 - Sketch of geometry D. (Author's own).

- **Geometry E:** Checkerboard for a staggered heat path (Figure 24);

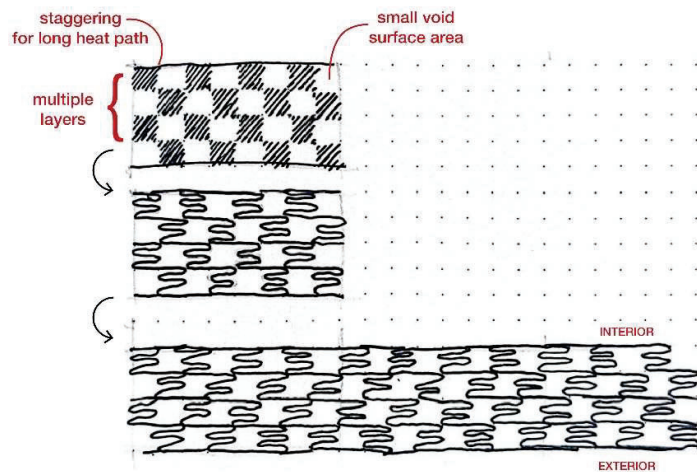


Figure 24 - Sketch of geometry E. (Author's own).

- **Geometry F:** Leaf-shaped cells for branching (Figure 25).

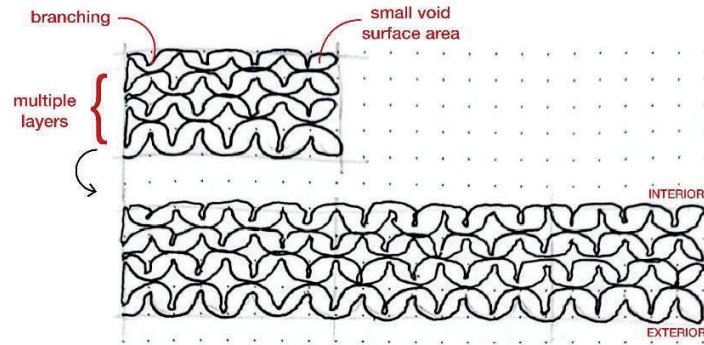


Figure 25 - Sketch of geometry F. (Author's own).

However, upon further development and practical study, Geometries D, E and F were discontinued for development due to concerns regarding their feasibility, considering the 7 cm layer thickness/40 cm wall thickness, as well as their printing time (specifically for E and F). Therefore, the finalized options were further trimmed down to three, as shown in Figure 26:

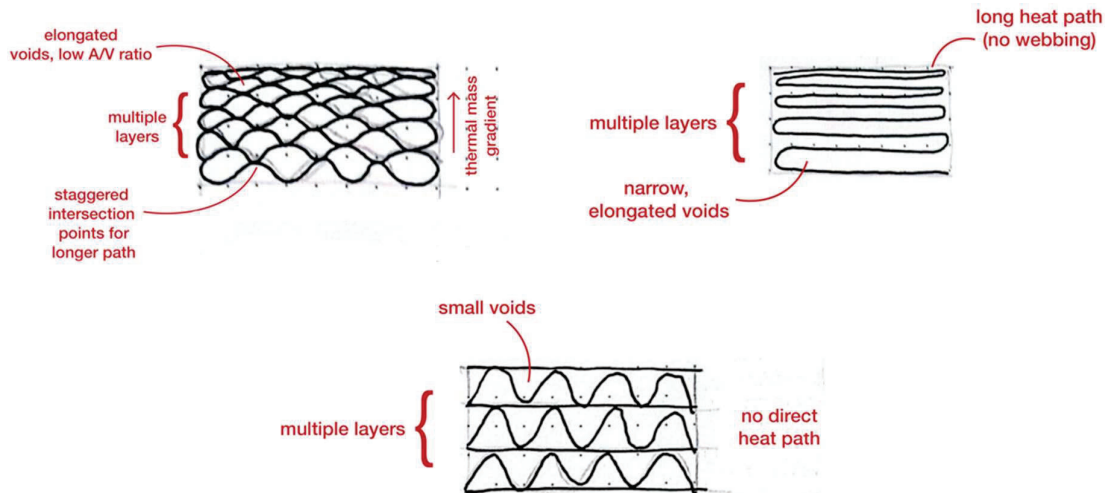


Figure 26 – Sketches of finalized geometric base options. (Author's own).

While the finalized options each focus on a particular aspect or principle of thermal performance – such as long heat paths for thermal lag, closed cells for insulation, or a subdivided void structure – it is important to note that all the selected options inherently combine multiple thermal principles in their design, allowing a more holistic performance.

3.3. PARAMETRIZATION OF GEOMETRIES IN GRASSHOPPER

3.3.1. INTRODUCTION TO RHINOCEROS AND GRASSHOPPER

The finalized geometries were then translated into parametric base models using the Grasshopper plugin within the Rhinoceros software environment, allowing for their systematic iteration into different levels of complexity, which is necessary for the succeeding simulation stage.

Rhinoceros (also known as Rhino) is a 3D computer-aided design (CAD) software that is known for its accuracy, flexibility and ability to handle complex or free-form geometries. NURBS-based modeling, which allows for accurate representation of curves and surfaces, makes it a good fit for architecture, engineering and industrial design applications [99].

Grasshopper on the other hand, is a visual programming plugin within Rhino that facilitates the use of parametric design. This means that instead of manually modeling geometry, algorithms are defined by connecting graphical components, which then allow for the generation of complex, adaptable geometries that can be adjusted through input parameters [100]. This workflow can increase design flexibility, and support automation, optimization, and iteration, making it ideal for this study which involves numerous geometries. This parametrization also enables sensitivity analyses to be done for design variables, including the number of layers, void sizes, layer thicknesses, wall thicknesses, and overall geometric complexity.

In addition to these benefits, Rhino and Grasshopper were chosen for the study as they are widely used in the 3D printing space, evidenced by the previously mentioned literature review. They also possess a wide array of available plugins for specialized tasks, such as mesh creation (TRmesh), heat transfer solving (TRfem), and 3D printing G-code generation (Termite). Finally, developing a parametric model also more easily lays the foundation for future work, allowing for further iterations and expansions, as needed.

3.3.2. PARAMETRIZATION RULES AND INPUT PARAMETERS

The main boundary constraints applied during parametrization include the following:

- **Thickness of wall element:** 40 cm from centerline to centerline, not restricted to straight wall profiles. In the case of wave geometries, the average/neutral axis of these waves served as the points of measurement. With this, a 40 cm deep rectangle served as the base for the wall geometries. Wave geometries were allowed to oscillate about these exterior bounds, meaning some sections would exceed 40 cm in thickness;
- **Print layer thickness:** 7 cm, a dimension derived from existing commercial 3D printers for earth-based materials, proven ideal for onsite printing due to structural and buildability considerations. The 7 cm layer thickness is drawn from the centerline of the print path, meaning there is 3.5 cm on each side of the line;
- Another set of geometries was generated using a 5 cm print layer thickness, to investigate the influence of more intricate geometries on thermal performance;
- A representative **1m x 1m** square portion of the wall was modeled to standardize comparisons;
- **Printing paths** were designed to be **continuous**, explicitly avoiding 90-degree corners, especially when connecting layers. This minimizes print stopping, which leads to reduced print time and material wastage;

- A **minimum radius of 50 mm** measured from the centerline was maintained for all curves to ensure path continuity, based on the 1:1 printing process of earth in existing projects;
- At points of intersection within the geometry, layers only touched at **one tangent point**, preventing potential overlapping conflicts during actual printing.

The slider inputs within the Grasshopper scripts allowed for the control of the following parameters:

- Wall height;
- Wall depth;
- Wall length;
- Fillet radius;
- Layer thickness (or filament width);
- Horizontal proportionality factor (establishes the number of divisions of the curve, determining the frequency of the wave geometry on the horizontal axis);
- Vertical proportionality factor (establishes the number of divisions of the curve, determining the frequency of the wave geometry on the vertical axis).

Individual Grasshopper scripts were created for each geometry, shown below.

3.3.3. GEOMETRY A: CLOSED CELL GEOMETRY

Figure 27 below shows an overview of the entire Grasshopper script for the creation of Geometry A.

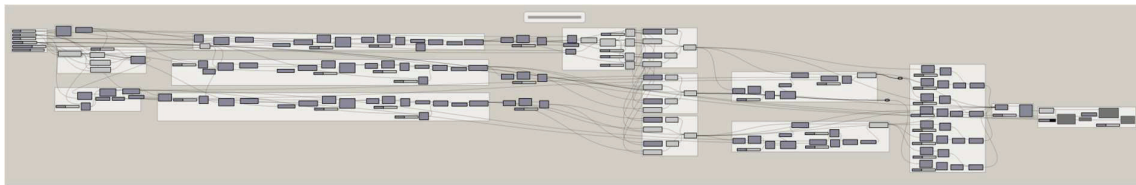


Figure 27 – Overall Grasshopper script for geometry A. (Author's own).

The overall premise of the script is to start with a 40 cm deep rectangle, with a 1 m length, which acts as the guide for the geometry's creation. The inputs to create these dimensions are shown in Figure 28. The 40 cm depth is then divided by 5 points determined by the expressions below, which were derived arithmetically, as shown in Figure 29.

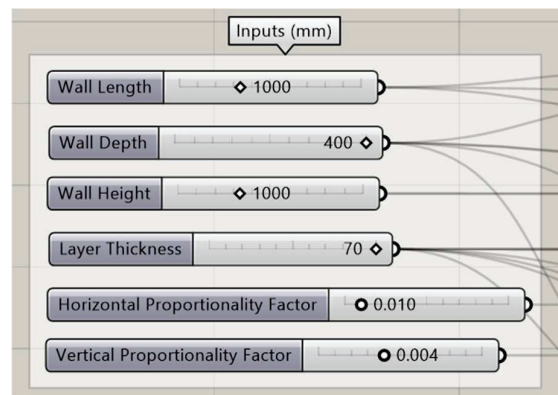


Figure 28 – Script inputs. (Author's own).

These base waves were then copied vertically, in order to produce a wave-like loft. However, to create vertically closed cells which are part of the geometry's concept, straight lines on the interior side of the wave's bounding box were created, alternating with the wave geometries. For this, a vertical proportionality factor was used to divide the vertical height of the geometry (1 m) into five points, shown in Figure 31. This ensures that the aspect ratio of the voids is greater than 2, as recommended by Briels *et al.* [9]. At the same time, based on standards from Havelar, the cantilever of a layer over its preceding layer was at a maximum of 1/3 of the layer thickness, to ensure buildability. The wave geometries were then placed at the first, third, and fifth points, while the straight lines were placed at the second and fourth points. Lofting these curves creates an undulating surface that, when mirrored, creates air cells that are closed horizontally and vertically. Therefore, a total of five lofts were created, one for each layer of the geometry, which were then connected at the sides with a fillet radius to create a continuous print path. The result at this point is one continuous surface comprised of 5 horizontally and vertically undulating layers, all connected at the sides, as shown in Figure 32.

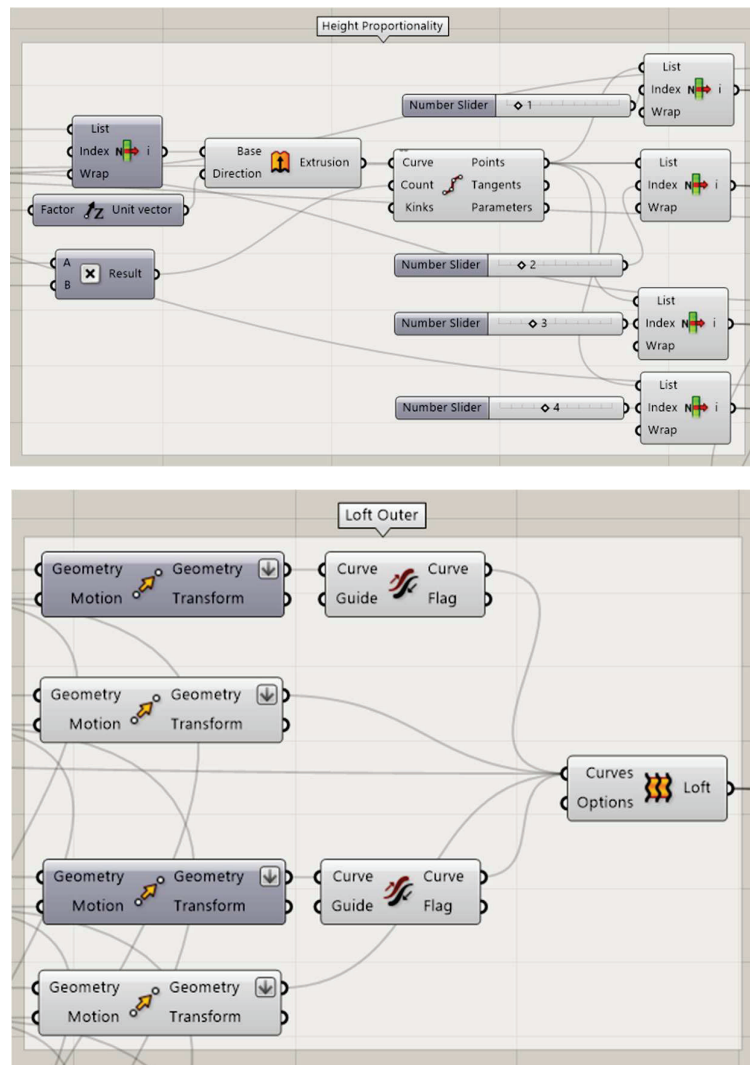
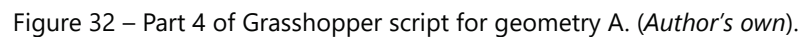


Figure 31 – Part 3 of Grasshopper script for geometry A. (Author's own).



1. *Contouring* – by inputting the desired layer height, contours may be used to create the layer-by-layer print paths needed for the g-code for 3DP. At the same time, these contours may be used to create pipes, which can create a visual representation of the extruded material texture of the 3D-printed wall geometries.
2. *Surface offset* – may be used to create the simulation geometries for input in TRmesh and TRfem, which are a simplified version of the 3D-printed walls that do not feature the actual printed texture. This is done to represent the geometries in a simplified way, to reduce computational time and processing power required by the simulations.

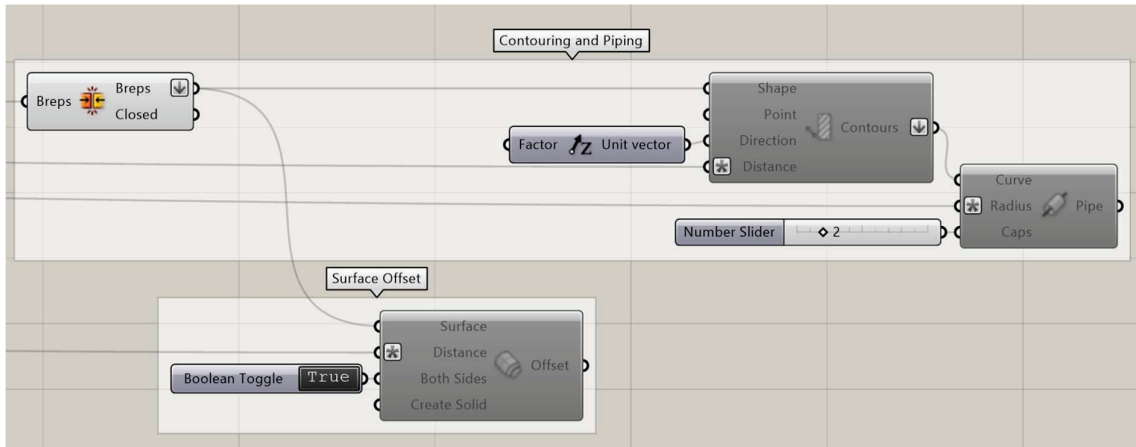


Figure 33 – Part 5 of Grasshopper script for geometry A. (Author's own).

Note: This script also has a version for 3 and 4 rows.

3.3.4. GEOMETRY B: MULTI-LAYER GEOMETRY WITH LONG HEAT PATH

Upon further study of geometry B, it was observed that applying the curvature to the layers to elongate the heat path was not feasible, given the fixed 40 cm wall depth parameter. Therefore, an alternative approach was applied – oscillating the otherwise straight lines would elongate the heat path as it introduces oblique angles, and at the same time can act to increase the structural stability of the component. Figure 34 shows the entire script for geometry B, as well as the inputs used for the script.

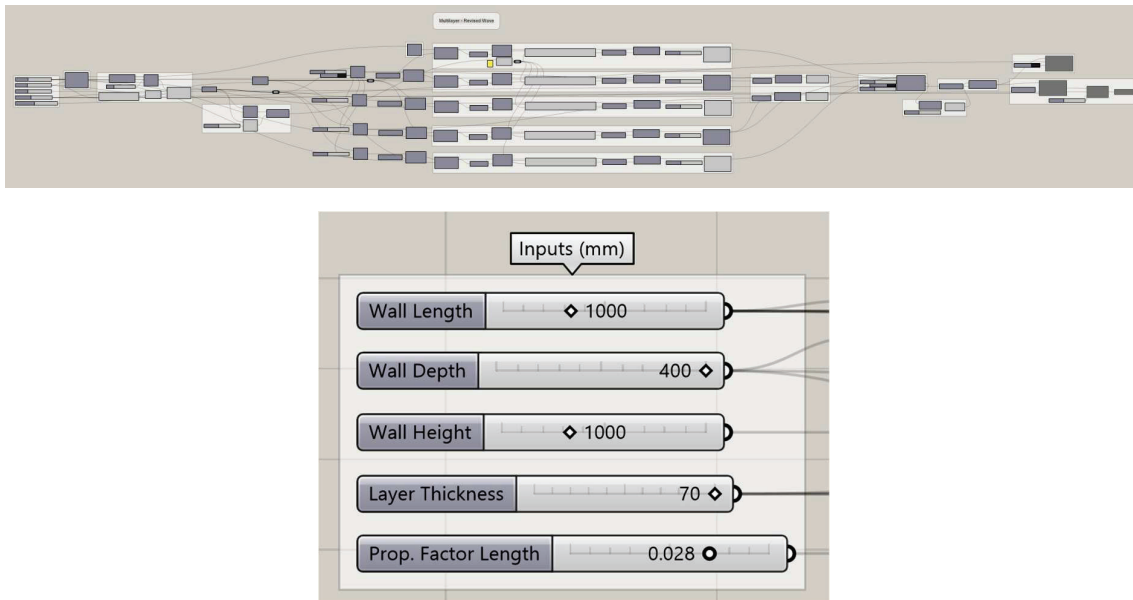


Figure 34 – Overall Grasshopper script and inputs for geometry B. (Author's own).

The script works similarly to that of geometry A in that it uses a rectangle with 40 cm depth and 1 m length as a guide for the geometry's construction. The depth of the rectangle is then divided according to the expression: $(0.675/T) \cdot (D/400)$ as shown in Figure 35, which creates a complementary link between the wall thickness and layer thickness, similar to geometry A.

3.3.5. GEOMETRY C: ALTERNATING SINUSOID AND STRAIGHT LAYERS

Figure 38 below shows the Grasshopper script for geometry C.

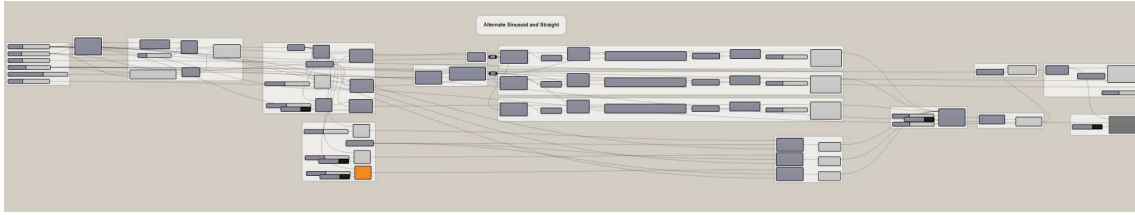


Figure 38 – Overall Grasshopper script for geometry C. (Author's own).

The script for geometry C follows the same logic: starting with a base rectangle, and dividing its depth according to the expression: $(0.675/T) \cdot (D/400)$. This is shown in Figure 39, as well as the inputs for the script.

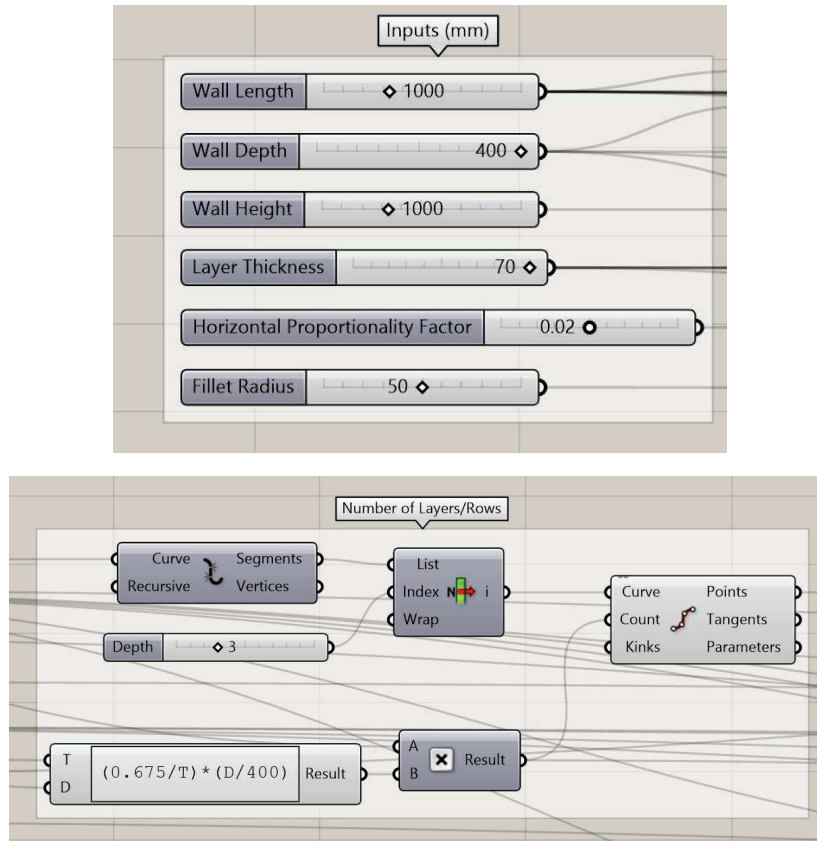


Figure 39 – Part 1 of the Grasshopper script for geometry C. (Author's own).

In contrast, it separates the division points into two: those for wave geometries and those for straight partitions, as shown in Figure 40.

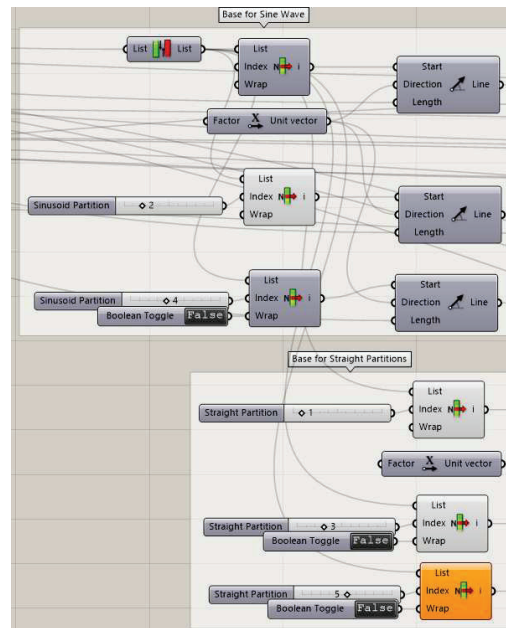


Figure 40 – Part 2 of the Grasshopper script for geometry C. (Author's own).

The wave geometries make use of the same parametrization components as those of geometry B, however using a different amplitude expression (Figure 41) to ensure that the waves touch the straight partitions to create closed voids. Three wave layers are created in this iteration.

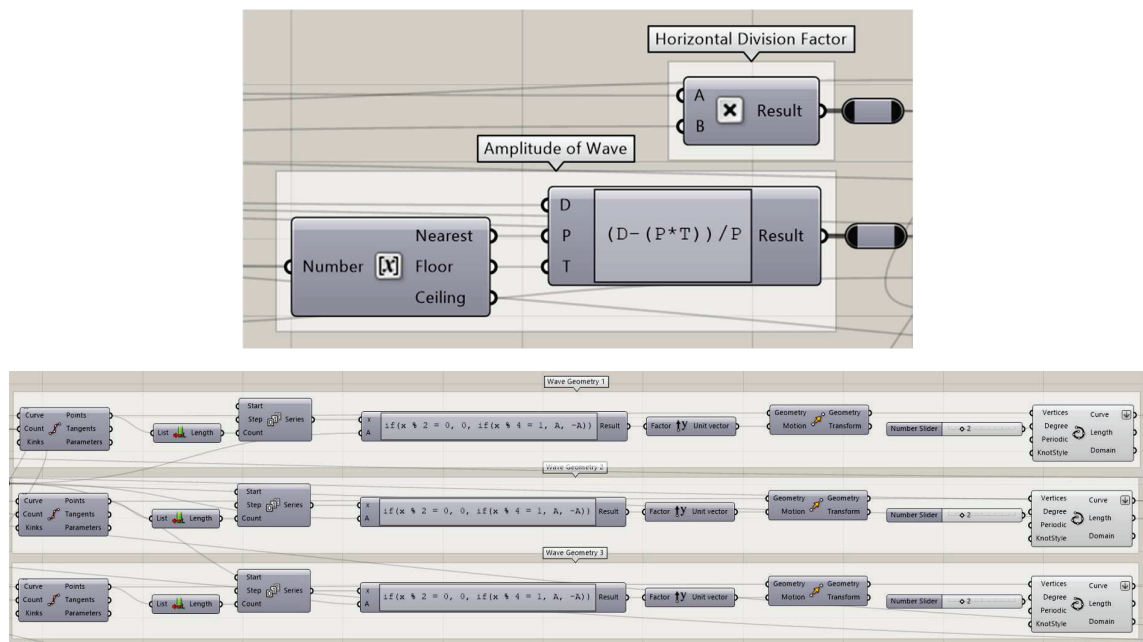


Figure 41 – Part 3 of the Grasshopper script for geometry C. (Author's own).

The straight partitions, in contrast, are created using SDL components. Finally, the layers are connected, filleted, vertically extruded, then either contoured and piped, or surface offset, similar to geometry B.

Note: this script also has a version for 3, 4 rows.

3.3.6. FINAL GEOMETRIES

The final base geometries are shown in the figure below, demonstrating the process from hand sketching to parametrization to piped volumes.

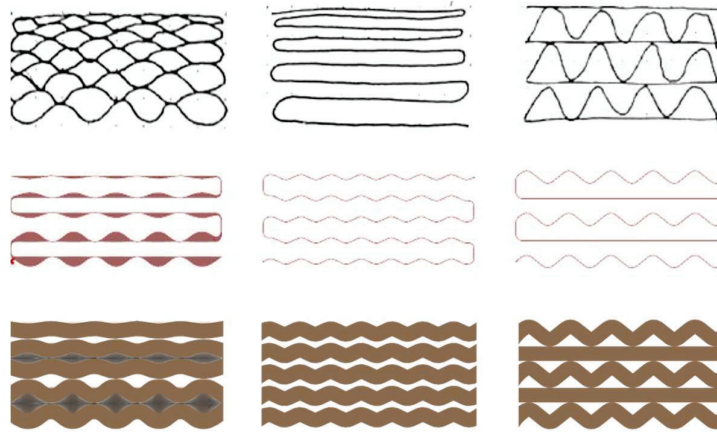


Figure 42 – Final base geometries. (Author's own).

3.3.7. ITERATION OF FINAL GEOMETRIES

To evaluate the influence of geometric complexity on thermal performance, the iteration framework of the study prioritized a sensitivity analysis on each of the three base geometries. For each geometry, three levels of complexity were generated through manipulation of Grasshopper input sliders. These levels (low, medium, and high complexity) make it possible to assess how increasing degrees of geometric intricacy can affect performance metrics such as U-value and print path length or volume.

In order to isolate the effects of geometric complexity, each iteration maintained certain items constant, as previously mentioned:

- Base wall thickness: 40 cm
- Layer thickness: initially fixed at 7 cm, which is typical for onsite printing. A secondary set of iterations at 5 cm layer thickness was also created to assess the difference in performance with a different layer thickness (which would potentially allow for more complex designs), effectively doubling the total number of iterations.

Variations were then introduced in the following aspects:

- Number of layers (e.g. 3, 4, 5, or 6)
- Number of internal voids
- Size of voids

Different complexity levels were considered:

1. *Most complex iteration*
 - a. Highest print path length (and therefore printing volume, printing time, and embodied carbon)
 - b. Highest number of voids
 - c. Smallest void sizes
 - d. Highest number of layers

2. Least complex iteration

- Shortest print path length
- Lowest number of voids
- Largest void sizes
- Lowest number of layers

3. Intermediate complexity iteration

- Balances the print path length, complexity, void structure, and number of layers between the most complex and least complex iterations.

The study evaluated the three base geometries, each developed at three levels of geometric complexity, with an additional iteration included for the least complex version of geometry C to investigate the effects of thermal bridging, resulting in 10 iterations. Each was assessed at two print layer thicknesses (5 cm and 7 cm), yielding 20 in total. These were divided evenly into two sets: 10 with 7 cm layers and 10 with 5 cm layers.

In addition, two reference wall geometries were included: (1) a solid earth wall (representing historical construction methods such as monolithic rammed earth), and (2) a conventional cavity wall. Each geometry followed a consistent identification convention. For example, 7A-3 refers to a geometry with a 7 cm layer thickness, based on geometry A and containing 3 layers. Due to the fixed wall depth, a maximum of 5 layers could be achieved in the 7 cm cases, while the 5 cm cases allowed for 3 to 6 layers. Figure 43 shows the summary of this framework for iteration, while their dimensions and 3D images are shown in Table 7. Isometric images simulating the printed texture and wall terminations can be seen in Annex A.1.

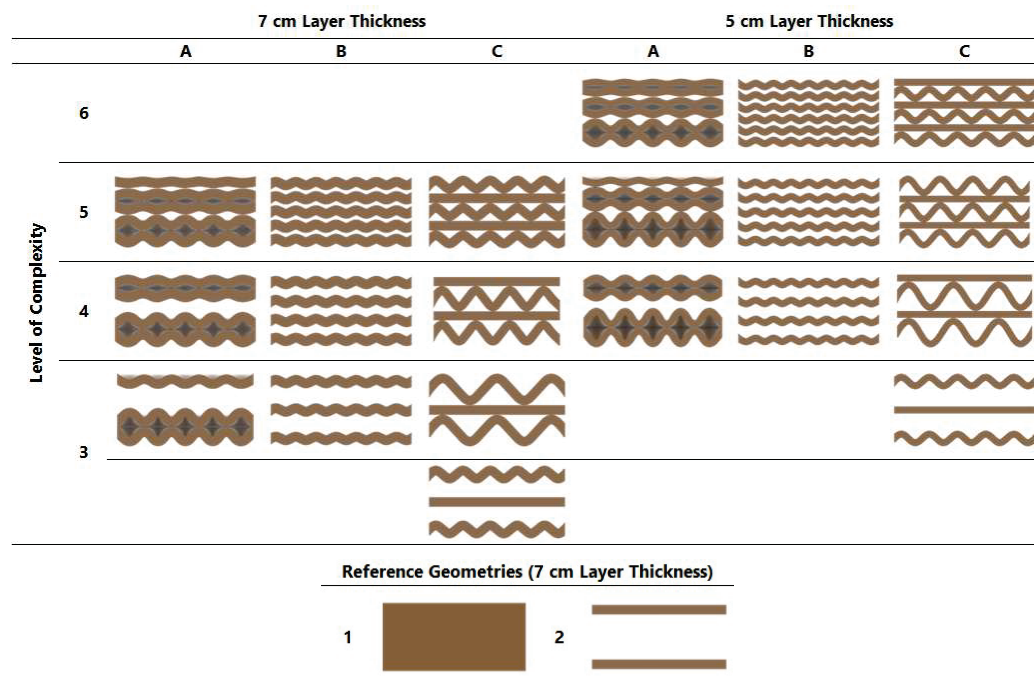
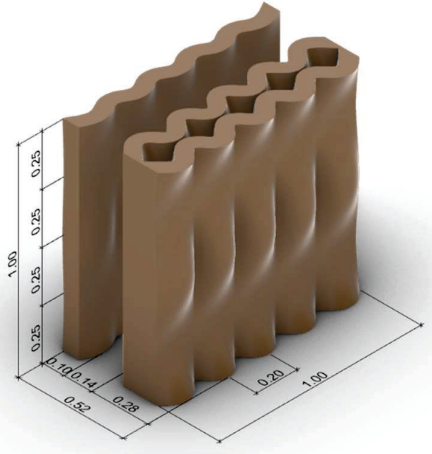
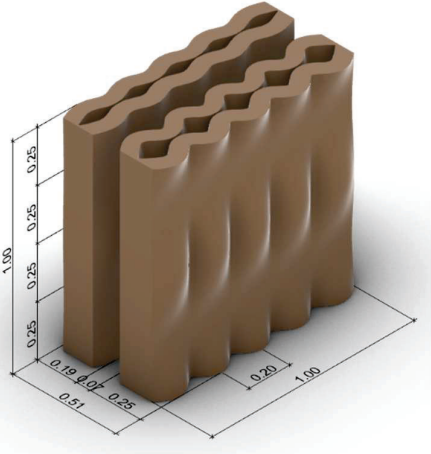
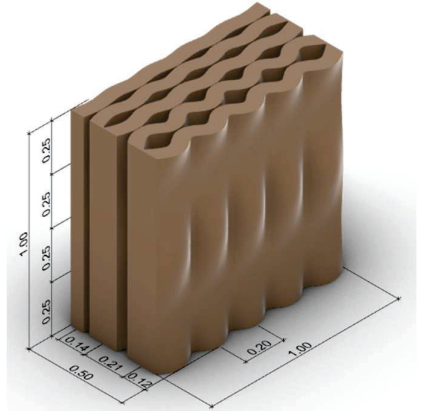
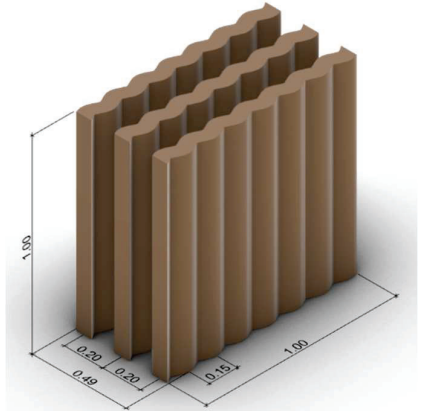
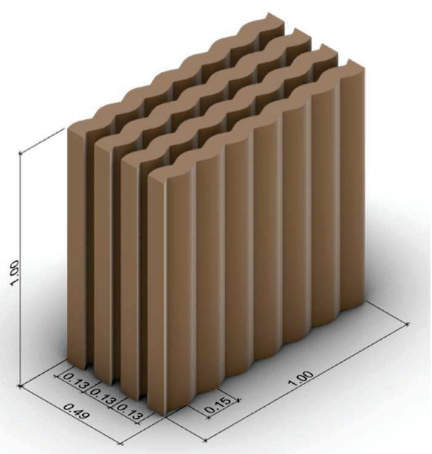
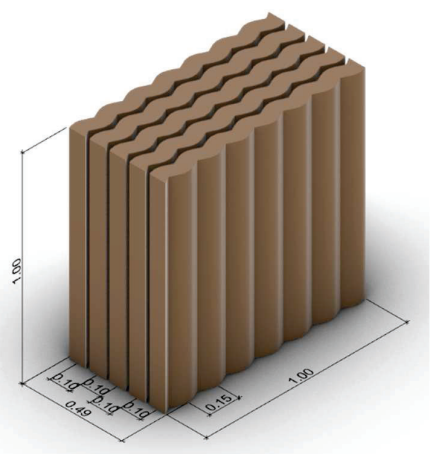
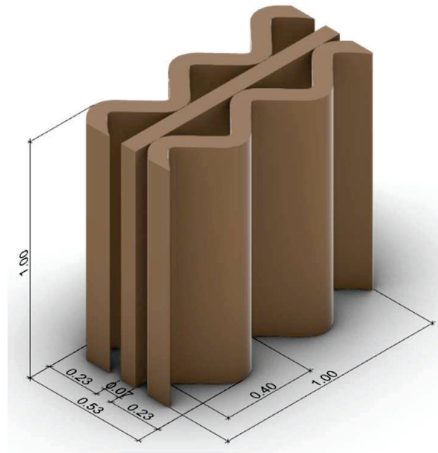
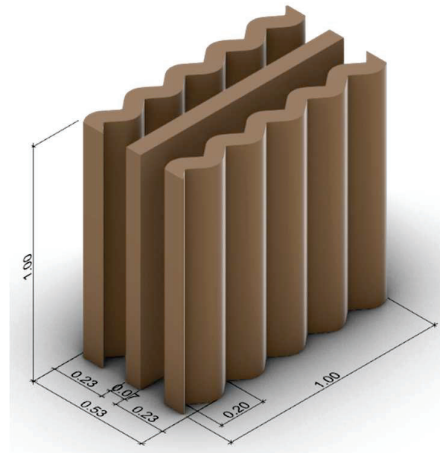
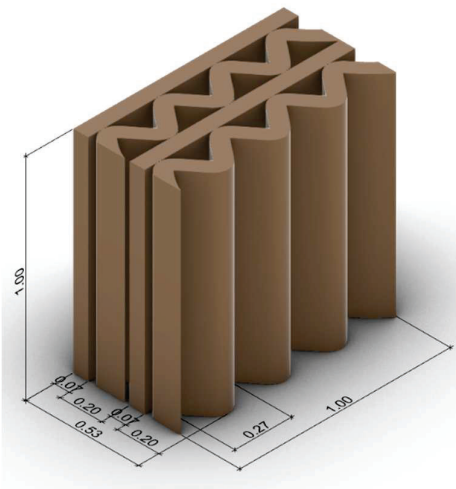
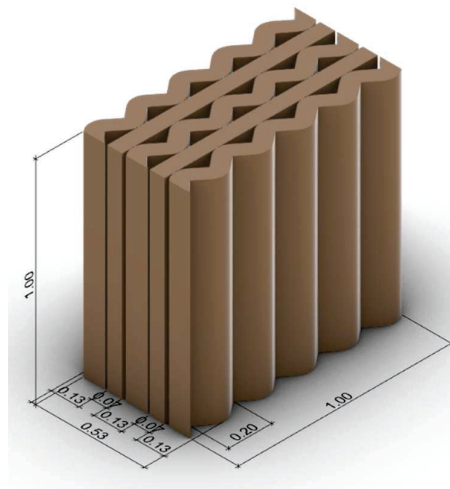
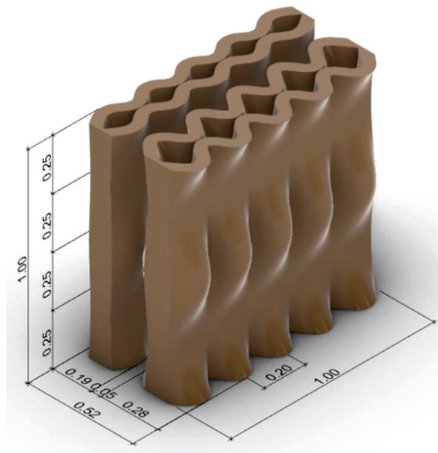
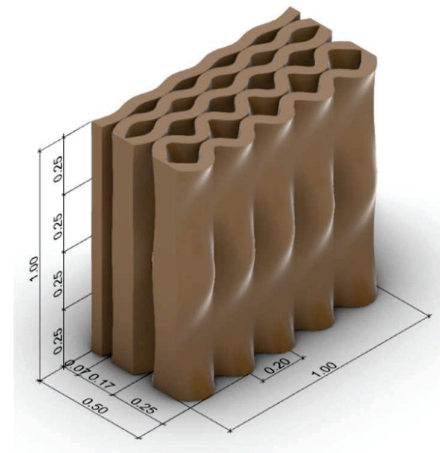


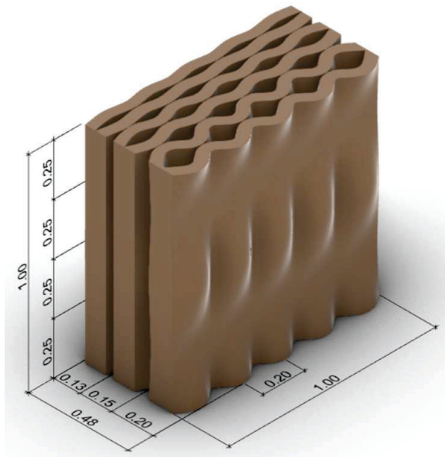
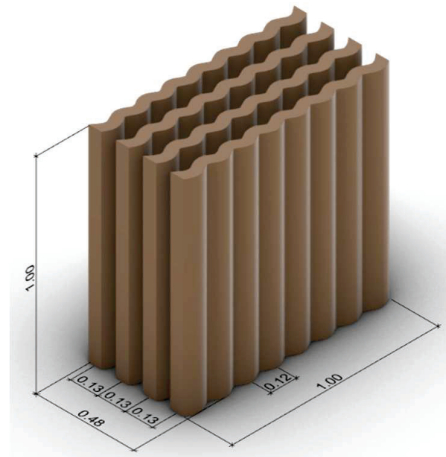
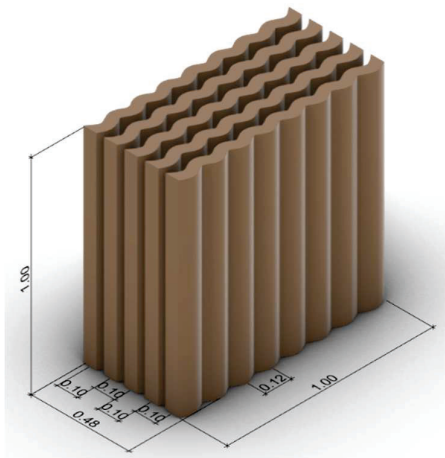
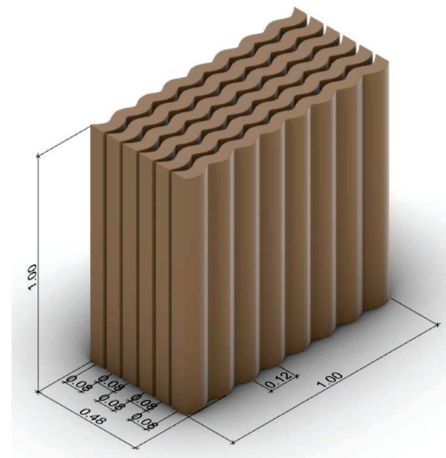
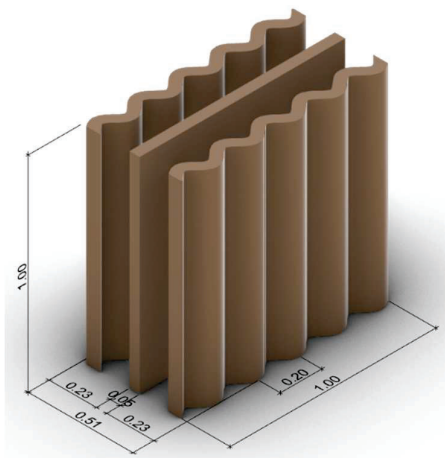
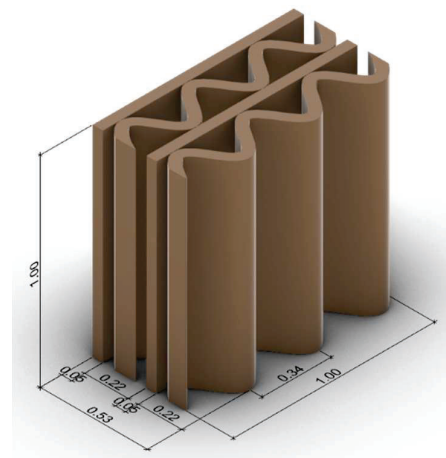
Figure 43 - Overview of all analyzed geometric iterations.

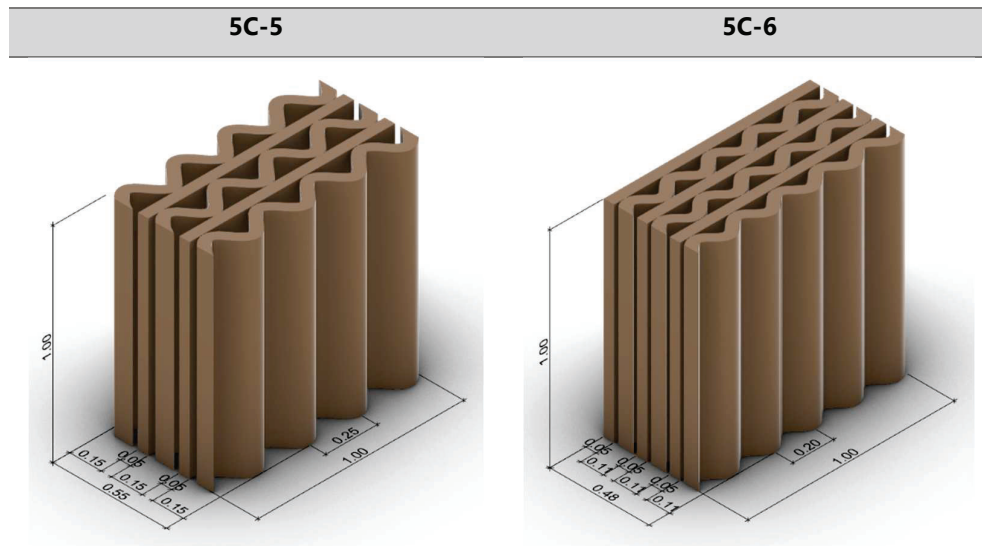
Initially, both multi-objective and single-objective optimization approaches were planned using Grasshopper plugins such as Wallacei and Galapagos. However, these methods proved infeasible due to limitations within the TRmesh/TRfem simulation workflow. Further details on these constraints are provided in Annex A.2.

Table 7 – 3D images and dimensions of geometric iterations for simulation (units: meters).

7A-3	7A-4
	
7A-5	7B-3
	
7B-4	7B-5
	

7C-3**7C-3A****7C-4****7C-5****5A-4****5A-5**

5A-6**5B-4****5B-5****5B-6****5C-3A****5C-4**



3.4. NUMERICAL SIMULATION WITH TRMESH AND TRFEM

3.4.1. METHODOLOGY

Following the iteration of the geometries, numerical simulations were conducted with the goal of calculating the thermal transmittance (U-value) of each geometry and respective iteration. These simulations provide a quantitative comparison of the thermal performance of the geometries. Steady-state heat transfer analysis was carried out using the TRmesh and TRfem plugins in Rhino, using a validated setup to ensure the consistency of results.

This stage of the research aimed to answer the following questions:

- Which geometric iterations of 3D-printed components exhibit the lowest U-values?
- What underlying thermal concepts drive their good performance?
- How do their results compare with the reference geometries?

TRmesh (V0.2.9981.3902) is a tetrahedral meshing plugin for Rhino, which can generate high-quality volumetric meshes for thermal simulations. It is built on the openNURBS C++ API and incorporates an advancing-front algorithm optimized through Rhino's native distance-to-brep functionality [101]. The development of TRmesh is based on the work of Fuchs [101], which explored the importance of mesh quality in conductive heat transfer analysis of thermal bridges. By embedding the meshing process within the Rhino environment, TRmesh can enable workflows direct from geometry to analysis, significantly reducing the time and effort between design iteration and simulation.

The primary benefits of TRmesh include [101]:

- Direct integration with Rhino, eliminating the need to export geometries to external meshers and maintaining continuity across the design and simulation loop, even for complex geometries;
- Error reduction, as its automated and adaptive meshing directly maintains the design's integrity, decreasing the chances of inconsistencies between the modeled and analyzed components;

- Performance efficiency, due to the plugin's reliance on Rhino's internal API, which accelerates distance queries and mesh construction, supporting fast analyses during early-stage design.

The tool's usage involves the selection of one or more adjacent, non-overlapping solids, and specification of a target edge length within the suggested interval. The tetrahedral mesh is then generated within seconds to minutes, depending on the geometry size and resolution.

TRfem (V0.2.8952.9873) on the other hand is a volumetric heat transfer solver designed to work with tetrahedral meshes generated in Rhino, acting as a companion tool to TRmesh. Unlike other energy modeling tools, TRfem performs a three-dimensional or volumetric steady-state conduction analysis across the tetrahedral mesh [101]. This approach enables a more localized understanding of thermal behavior, especially in the analysis of complex geometries typical of 3D-printed walls.

The TRfem solver requires the following inputs:

- A Rhino quad mesh with each quad representing a tetrahedron;
- A list of tetrahedral references mapping each tetrahedron to a thermal conductivity value;
- A list of thermal conductivity values, representing each unique material in the mesh (e.g. solid material or air voids);
- Vertex indices designated as hot (e.g., interior-facing surfaces exposed to heated air) and cold (e.g., exterior-facing surfaces exposed to cold air).

All remaining vertices are treated as adiabatic boundaries, meaning they are in contact with insulating conditions and do not contribute to heat exchange. This boundary condition setup aligns with the principles of thermal bridge analysis, in which conductive elements are modeled in contrast to insulated surroundings [101]. The resulting temperature field will have a gradient that goes from cold to hot vertices, with no heat transfer across adiabatic boundaries. TRfem's simulation results include temperature fields and isosurface visualizations, which are helpful to understand heat flow through complex geometries.

TRfem is fully compliant with UNE-EN ISO 10211:2017 [102]. At the same time, its algorithm and implementation have been documented in the peer-reviewed work by Fuchs [101], ensuring the reliability of the simulations. Figure 44 gives an overview of the entire TRfem Grasshopper script, with the main components annotated with red labels.

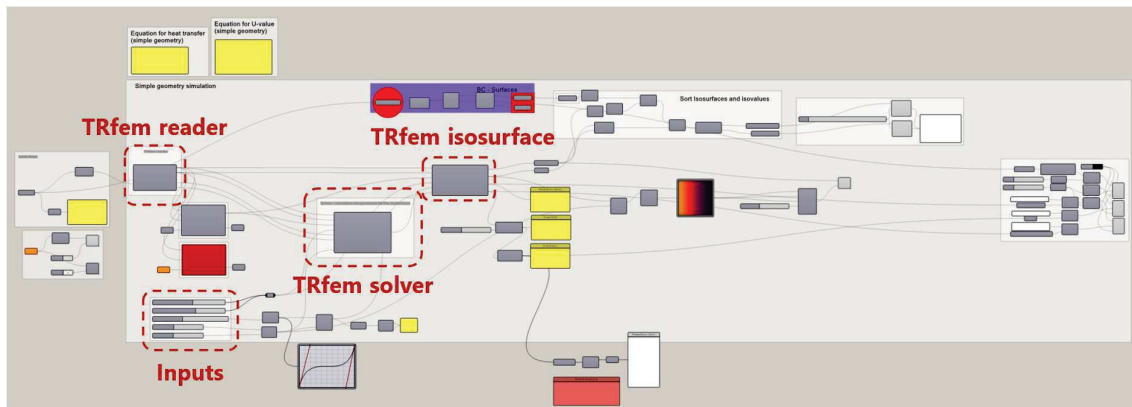


Figure 44 – Screenshot of TRfem Grasshopper script.

The script for TRfem includes the following main components:

- Inputs – includes material conductivities, number of isosurfaces, and boundary temperatures (Figure 45);

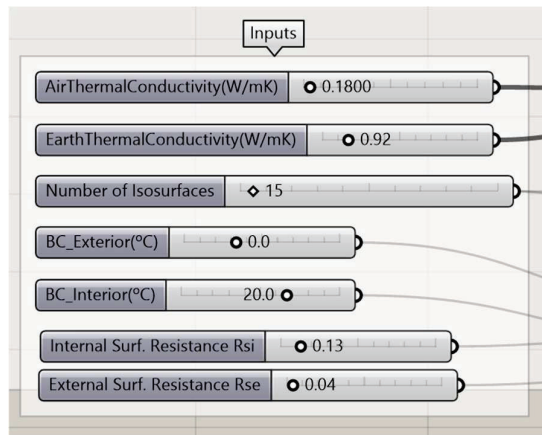


Figure 45 – Screenshot of TRfem inputs used.

- TRfem reader – reads the tetrahedron mesh from TRmesh (Figure 46);
- TRfem solver – calculates temperatures for the isosurfaces, with inputs such as the vertices of the mesh, the tetrahedral indices, the conductivity list, hot and cold vertices, and boundary temperatures (Figure 46);

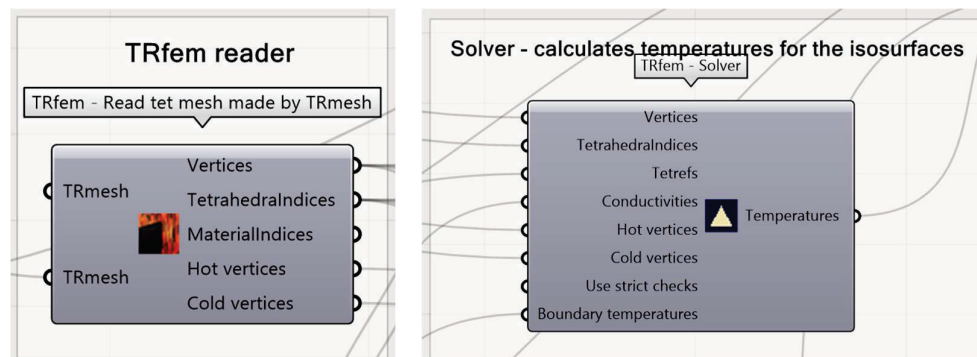


Figure 46 – Screenshots of TRfem reader and solver components.

- TRfem isosurface component – visualizes the isosurfaces (surfaces computed with equal temperature), and outputs thermal loss and absolute resistance (Figure 47).

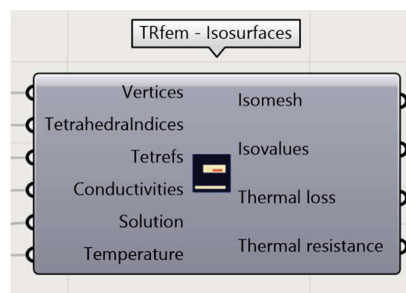


Figure 47 – Screenshot of TRfem isosurface component.

3.4.2. RATIONALE FOR SOFTWARE SELECTION

The study's methodology utilized the TRmesh/TRfem workflow mainly for the following reasons:

- Its suitability for 3D volumetric simulation, which can capture the thermal performance in geometries where there are variations in three dimensions (3D). The studied 3D-printed geometries feature voids and profiles that may affect heat flow not only on the horizontal axis but also on the vertical axis. 2D simulations might disregard these mechanics and end up with incomplete or misleading results of thermal performance;
- Its integration within the Rhino/Grasshopper environment allows for real-time feedback;
- Its low computational demand enables quick iterations of complex 3D geometries, which is especially useful for early-stage design.

Prior to using TRmesh and TRfem, several tools were also evaluated, but were deemed unsuitable for the current scope and timeline:

- LBNL THERM - Limited to 2D simulations, making it incompatible with geometries that vary along the vertical axis;
- ANSYS, COMSOL, ABAQUS – While these FEM software are commonly used for their robustness and accuracy, they can require significant computational resources and time, present steep learning curves, and are more used for full-scale simulations rather than early-stage design exploration. Further, integration with Rhino/Grasshopper-generated complex geometry is not streamlined and can result in meshing errors;
- Ladybug and Honeybee – these Rhino plugins are more commonly used for external energy and daylighting analysis and are not equipped for detailed internal heat transfer modeling.

3.4.3. TRFEM HEAT TRANSFER PRINCIPLES

TRfem primarily models conductive heat transfer, focusing on quantifying heat loss, often referred to as "thermal loss" or "energy loss," and is expressed as thermal dissipation [101]. This method specifically applies to stationary (steady-state) conditions and can be used to analyze non-uniform, isotropic materials with complex geometries. While steady-state analyses simplify transient or dynamic thermal behavior, they can provide a robust basis for comparing the performance of different geometries, especially for early-stage designs.

The main premise of TRfem's calculations is the solution of steady-state heat transfer, as expressed in Equation (1). This equation assumes no time-dependence and excludes any internal heating or cooling within the thermal bridge material, with heat transfer occurring solely through the boundaries. This simplification aligns with the principle of energy conservation in a thermal context, which states that the divergence of the heat flux within the thermal bridge is zero [101].

$$\nabla \cdot (\kappa \nabla u) = 0 \quad (1)$$

In this equation, u represents the temperature field (a scalar field), and κ is the thermal conductivity (also a scalar field, which can vary with the material). ∇ serves as the gradient operator when applied to a scalar field (like u) and the divergence operator when applied to a vector field (such as $\kappa \nabla u$, which represents the heat flux). This equation mathematically expresses that the divergence of the heat flux is zero, indicating that there is no internal heat generation or absorption within the material [101].

The calculation is performed under the following boundary conditions [101]:

- *Dirichlet boundary conditions* - these conditions apply on the interior and exterior facing surfaces (S), where $u = u_0$. Here, u_0 denotes prescribed temperatures (e.g. 20 °C on the interior and 0 °C on the exterior). This sets the fixed temperature conditions at the boundaries of the wall element;

- *Neumann boundary conditions* - these are applied to the remaining boundary surfaces ($\partial\Omega-S$), expressed as $\partial_n u = 0$ (or $\langle \nabla u, n \rangle = 0$). This indicates that no heat flux occurs across these surfaces. Surfaces adjacent to surrounding structures are assumed to be perfect insulators. This setup ensures the calculation focuses on the predominant heat flux from the inside to the outside through the wall section.

Once the temperature field (u) is obtained through solving the steady-state heat equation, other quantities are derived [101]:

- Thermal flux - calculated as $\kappa \nabla u$;
- Thermal dissipation - approximated by the surface integral $\oint \kappa \nabla u \cdot dS$ over all interior surfaces, quantifying the total heat loss from the system;
- Thermal conductance - obtained by dividing the thermal dissipation by the temperature difference ($T_1 - T_2$) across the boundaries.

3.4.4. TRFEM SIMULATION INPUTS AND OUTPUTS

To perform the simulation, the following input data must be specified within the TRfem script:

1. Mesh – a tetrahedral mesh generated by TRmesh that contains information on both hot and cold vertices;
2. Boundary temperatures (interior and exterior);
3. Number of isosurfaces – determined by the validation carried out in Section 3.4.5;
4. Thermal conductivities:
 - Earth material: conductivities were taken from prior studies that analyzed the 3DPE mix intended for this study (composed of water, earth, and kraft paper fibers from cement bags);
 - Air voids: thermal conductivities were determined in accordance with UNE-EN ISO 6946:2021 [15].

To assign the correct conductivity for the air voids of air layers:

- Air void dimensions were measured (in Grasshopper);
- The thermal resistance and the corresponding equivalent thermal conductivity of air voids were calculated based on UNE-EN ISO 6946:2021 [15], using inputs such as air void thickness, width, and area.
 - For geometries wherein the air voids are not regularly enclosed by waves or cells, therefore creating long and narrow regions of air when long lengths of wall are considered (e.g. Geometry B3, B4, B5, C3A, and some voids of A3 and A4), the study takes resistance values from the "horizontal" column of Table 27 (Annex A.3), given the horizontal direction of heat flow considered for wall components.
 - For geometries where internal air voids do not meet the requirements of Section 6.9.2, Annex D (Annex A.3) was used to determine the thermal resistance of the airspace.
 - Once the thermal resistance of the airspace is obtained, the thickness of the air void can be divided by R to obtain the thermal conductivity to be inputted in TRfem.
 - This method provides a means to ensure that non-uniform air cavities are included in the thermal model and simulations, as they play a significant role in the overall

performance of the wall. At the same time, it ensures that the resulting air conductivity captures the effects of conduction, convection, and radiation in the air voids, achieving a more realistic and holistic result.

- For geometries with varying void dimensions both horizontally and vertically (e.g., geometry A), thermal conductivities were calculated separately for the XY and YZ planes, then averaged to obtain one overall value, which was then applied to all the voids. This simplification was done due to high computational demands for assigning more than two material conductivities (e.g. for geometry A5, there were four air conductivities). Future studies can explore assigning individual conductivities to differently sized air voids within geometries.

TRfem gives the following outputs after the simulation:

- Thermal loss (Watts) - the total heat loss from the system under the set boundary conditions;
- Thermal resistance (Kelvin/Watt) - the absolute resistance of the component to heat flow. This value can be multiplied by the wall's surface area to obtain the conventional thermal resistance value, which can then be inverted to compute the U-value for comparative analysis;
- Isosurface diagrams - visualizations of the internal heat flow gradient, showing planes or surfaces containing tetrahedra of equal computed temperature. This can enable the qualitative assessment of the wall's thermal behavior and the role of geometry in it.

3.4.5. VALIDATION OF TRFEM RESULTS

To ensure the accuracy and comparability of the simulation results generated using TRfem, a validation procedure was conducted by comparing the plugin's outputs with analytically calculated U-values for two simplified wall geometries. The goal was to align the TRfem solver's results with theoretical expectations based on classical steady-state heat transfer formulas, as expressed in Equation (2). Where U is the thermal transmittance, in W/(m²·K), R_{tot} is the total thermal resistance, in (m²·K)/W, R_{si} is the internal surface resistance, in (m²·K)/W, R₁, R₂ ... R_n are the design thermal resistances of each layer, in (m²·K)/W, R_{se} is the external surface resistance, in (m²·K)/W.

$$U = \frac{1}{R_{\text{tot}}} \quad R_{\text{tot}} = R_{\text{si}} + R_1 + R_2 + \dots + R_n + R_{\text{se}} \quad (2)$$

Validation case 1: solid wall (47 cm earth)

A solid wall with a thickness of 47 cm was selected as the initial validation case. This thickness corresponds to the equivalent of a 40 cm wall plus two 3.5 cm outer layers (half the layer thickness of the interior and exterior wall paths). A thermal conductivity value of 1 W/(mK) was used for the earth material. The theoretical calculations determined a U-value of 2.13 W/(m²K), similar to TRfem's output of 2.13 W/(m²K).

The validated simulation considered the following conditions:

1. Wall surface area of 1 m × 1 m, as TRfem outputs absolute resistance (in K/W), which must be multiplied by the wall surface area to obtain thermal resistance (R-value in (m²·K)/W);
2. No surface resistances, as TRfem does not model surface resistances;
3. Mesh refinement: Meshing was adjusted using TRmesh to achieve the resolution needed to match the output with theoretical calculations.

Validation case 2: cavity wall (air and earth)

An additional case was used to validate TRfem's ability to simulate multi-material walls composed of air and earth. The setup consisted of a 33 cm air void between two 7 cm thick earth layers, resulting in a total wall thickness of 47 cm. For the purpose of validation, the thermal conductivity of the earth was set at 1 W/(mK), while the air conductivity considered was 0.0242 W/(mK) [71]. The wall dimensions (1 m × 1 m), mesh edge length range, and the exclusion of surface resistances were retained from the first validation test.

To examine the effect of mesh resolution on the simulation results, remeshing was performed at both higher and lower levels of detail. However, initial results showed a significant deviation from the analytical reference values. In response, the C# classification script (Annex A.6) was refined to reduce misclassification of tetrahedra, particularly at the interface between solid and air regions. A stricter classification rule was implemented, wherein the tetrahedron would be classified as air only if both its centroid and at least one additional vertex lay within the specified air brep. A new validation was then carried out using the mesh that previously yielded the closest result. This modification brought the simulation output significantly closer to the analytical calculation (Table 8).

While the result was closer, it was also observed that the number of isosurfaces affected the results, particularly in multi-material simulations. A sensitivity analysis revealed that using 15 isosurfaces reduced the discrepancy to 0.9%, which was considered acceptable for validation purposes. This is shown in Figure 48 and Table 9.

Table 8 – Influence of edge length (e.l.) range on the simulation results for case 2, mesh 5 with the refined C# code.

Mesh	Recommended e.l. range	# Tetrahedra	Mesh quality	# Isosurfaces	Thermal resistance (K/W)	Thermal transmittance (W/(m²K))	Analytical computation
With Air Gap							
1	0.25	19863	0.004	30	9.81	0.10	0.07
2	0.19	34444	0.002	30	11.24	0.09	
3	0.16	50541	0.002	30	11.2	0.09	
4	0.05	650089	0.0001	30	12.53	0.08	
With Air Gap & Refined C# Code							
5	0.05	650089	0.0001	30	13.13	0.08	0.07

# Isosurfaces	U-Value
{ 0 }	{ 0; 0; 0; 0 }
0 1	0 0.000022
1 2	1 0.039744
2 5	2 0.063541
3 10	3 0.071319
4 15	4 0.073748
5 20	5 0.074954
6 30	6 0.076165
7 50	7 0.077208
8 100	8 0.078227
9 200	9 0.079258

Figure 48 – Sensitivity analysis for the number of isosurfaces.

Table 9 – Sensitivity analysis for number of isosurfaces.

Mesh	Recommended e.l. range	# Tetrahedra	Mesh quality	# Isosurfaces	Thermal resistance (K/W)	Thermal transmittance (W/(m ² K))	Analytical computation
With Air Gap & Refined C# Code							
5	0.05	650089	0.0001	30	13.13	0.08	0.07
6	0.05	650089	0.0001	15	13.56	0.07	0.07

This change in results can be attributed to how TRfem's output is influenced by the distribution of the isosurfaces (especially in multi-material simulations), as the results are affected by the average of the isosurface temperature values. More isosurfaces can create higher concentration at the interfaces between two conductivities (see Figure 49), potentially shifting average values.

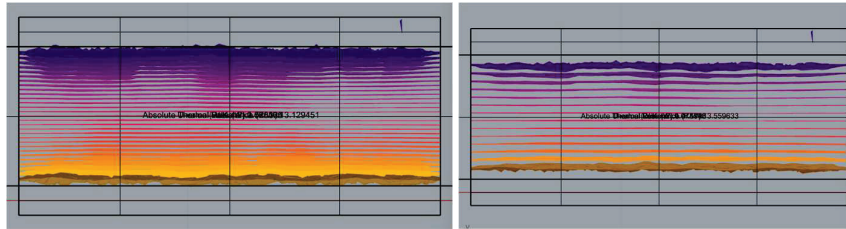


Figure 49 – Comparison of simulation results using the same mesh with different isosurface counts: 30 isosurfaces (left) and 15 isosurfaces (right), resulting to variations in the output.

With this insight, the same number of isosurfaces (15) was applied to the first validation test (solid wall), and the results remained consistent with the analytical calculation. This consistency is attributed to the use of a single material in the solid wall, making the simulation less sensitive to changes in the number of isosurfaces compared to multi-material configurations.

Although a mesh edge length of 0.05 produced the result closest to the analytical calculation, it is important to note that this resolution could not be reliably achieved across all geometries due to TRmesh limitations, specifically, errors encountered when meshing complex geometries at very fine resolutions. To address this, a coarser mesh with an edge length of 0.06 was validated to ensure compatibility across all geometry types (Table 10). This setting resulted in a 3% variation from the analytical calculation. Therefore, given this limitation, a $\pm 3\%$ margin of difference is expected in future experimental validation results.

Table 10 – Lower resolution mesh validation.

Mesh	Recommended e.l. range	# Tetrahedra	Mesh quality	# Isosurfaces	Thermal resistance (K/W)	Thermal transmittance (W/(m ² K))	Analytical computation
With Air Gap & Refined C# Code							
7	0.06	277001	0.001	15	13.08	0.08	0.07

The validation process led to a standardized set of parameters used for all succeeding simulations, to ensure consistency of results, shown in Table 11:

Table 11 – Finalized TRfem simulation settings and inputs.

Parameter	Validated value
Wall surface area	1 m × 1 m
Boundary temperatures	0 °C (cold surface), 20 °C (hot surface)
Number of isosurfaces	15
Mesh edge length	0.06

To ensure comparable simulation results, each geometry underwent a consistent workflow that integrates parametric modeling, volume preparation, mesh generation, and thermal simulation.

3.4.6. GEOMETRY PREPARATION IN RHINO

All geometries are developed using a parametric script in Grasshopper, as detailed in Section 3.3.3 to 3.3.5. To reduce computational demands during simulation, only the simplified solid volume of the geometry (no layer-by-layer texture) created by the surface offset component is used. After finalizing the parametric design, the resulting volume or brep is baked into Rhino for further preparation prior to meshing (more information on the preparation steps can be found in Annex A.4):

- A bounding box is generated around the entire geometry;
- A boolean difference operation is executed between the bounding box and the solid geometry;
- The resulting geometry represents the air volumes, extracted as breps for use in the simulation (Figure 50).

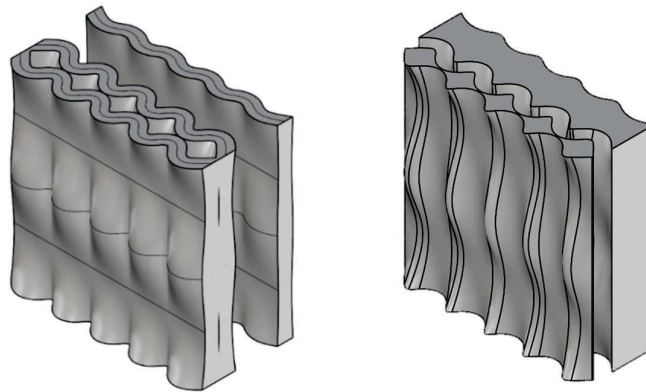


Figure 50 – The modeling geometry in Rhino: baked and prepared solid (left), and the resulting air breps (right).

3.4.7. MESH GENERATION WITH TRMESH

A boolean union of the solid and air breps is performed to create a unified volume. Using TRmesh, a tetrahedral mesh is then generated based on this unified geometry, applying the validated setup. The mesh is constructed using only the outer boundaries of the combined volume to produce a single, continuous tetrahedral mesh suitable for simulation (Figure 51). Common errors during this process are shown in Annex A.5.

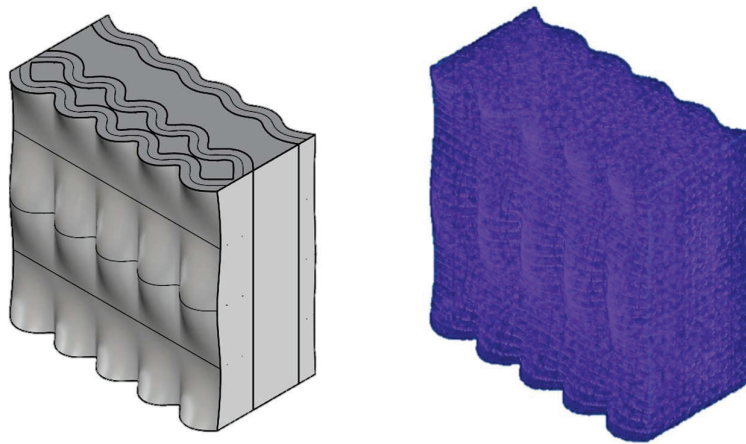


Figure 51 – Unified volume containing solid and air breps (left) and the resulting mesh from TRmesh (right).

If necessary, the mesh can be further refined by increasing peeling (removing vertices that are located outside the bounds of the geometry's brep). This process helps reduce the number of tetrahedra and increases overall mesh quality.

At this stage, the mesh settings or parameters can also be recorded for documentation, with a specific focus on the recommended edge length range, which was used as a constant across all geometry meshes for consistency (see Section 3.4.5. Validation of TRfem results).

Next, cold and hot surfaces are defined by selecting the mesh surfaces corresponding to the exterior and interior faces of the wall, respectively. All remaining surfaces are treated as adiabatic boundaries (Figure 52). The final mesh, along with its boundary condition assignments, is then baked into Rhino for input into TRfem.

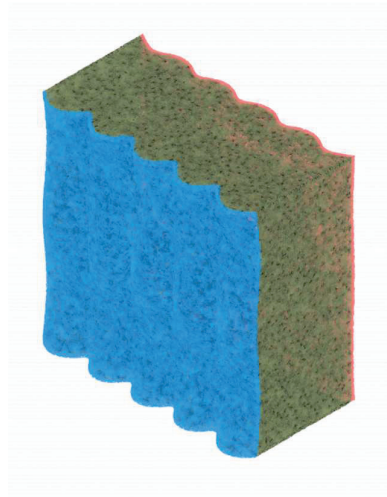


Figure 52 – Tetrahedral mesh with assigned boundary conditions: blue tetrahedra represent the exterior (cold) side, red tetrahedra indicate the interior (hot) side, and green tetrahedra correspond to adiabatic boundaries.

3.4.8. SIMULATION SETUP

In the Grasshopper TRfem script, the tetrahedral mesh from TRmesh and the air breps are used as inputs (see Annex A.6 for more information on the TRfem reader and the C# code). The following input parameters were then defined based on the validated setup (Figure 53):

- Boundary temperatures (interior and exterior): set to a constant 0 °C (exterior) and 20 °C (interior) for all simulations, following the simplified approach outlined in EN 15026:2023 [103] Annex D and supported by precedent studies;
- Thermal conductivities: assigned for both solid and air regions. The air conductivity is indexed first, followed by that of the solid (earth) material;
- Number of isosurfaces: specifies the resolution of heat transfer visualization;
- Internal and external surface resistances: added to the thermal resistance output to obtain a more realistic overall R-value.

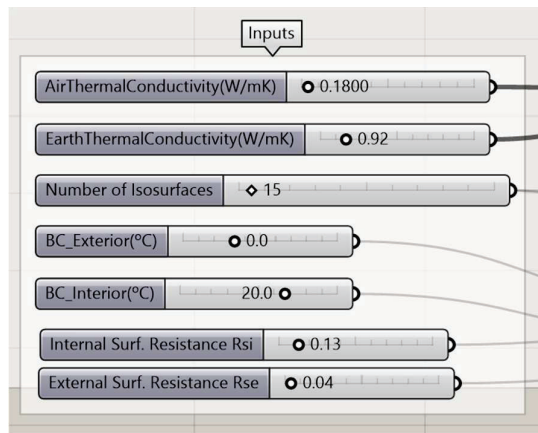


Figure 53 – TRfem simulation inputs.

The TRfem component solves the steady-state heat conduction equation using the prepared mesh and specified inputs parameters. Once finished, the solver outputs thermal loss and absolute resistance, which are used to calculate the U-value. The solving process typically takes between 5 to 30 minutes, depending on the complexity of the geometry.

Post-processing results (Figure 54):

- Absolute resistance (K/W) is obtained from the simulation output, which can be multiplied by the surface area (m^2) of the wall to get thermal resistance (R-value in $(m^2K)/W$);
- Surface resistances are added to the R-value in accordance with UNE-EN ISO 6946:2021 [15]. For simplification, values of 0.04 $(m^2K)/W$ (external) and 0.13 $(m^2K)/W$ (internal) were used;
- U-value is calculated as the inverse of the total thermal resistance, in accordance with UNE-EN ISO 6946:2021 [15];
- An isosurface diagram is also obtained from the TRfem component to visually represent the temperature gradient and heat flow throughout the geometry (Figure 55).

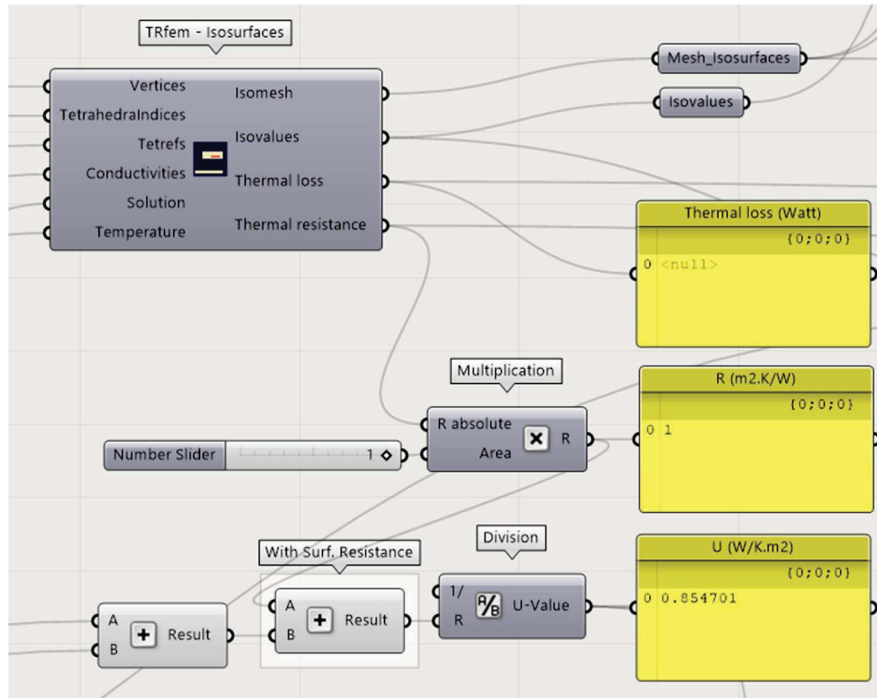


Figure 54 – Screenshot of TRfem output values and mathematical operations to obtain the U-value.

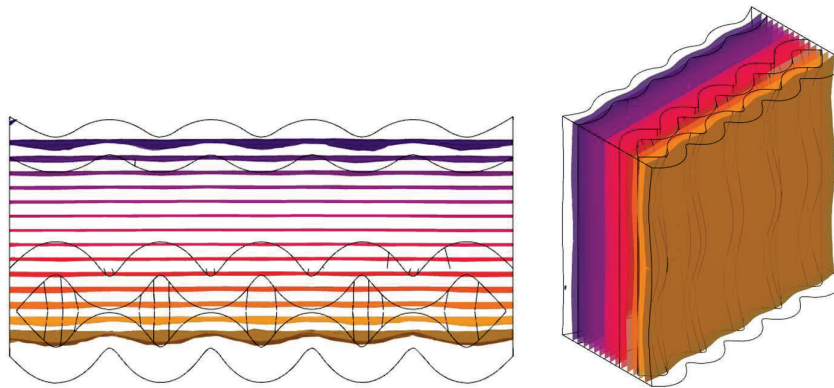


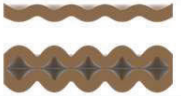
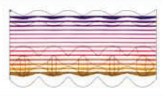
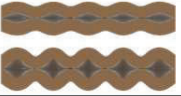
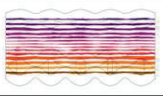
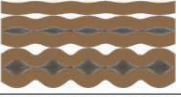
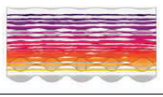
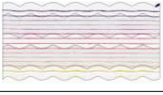
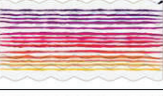
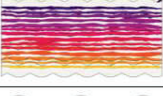
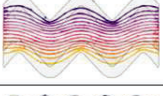
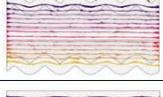
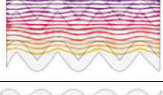
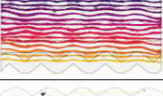
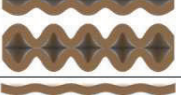
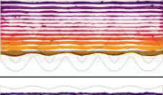
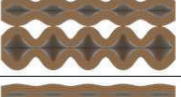
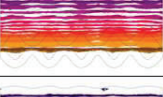
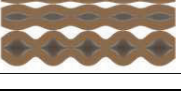
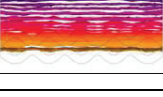
Figure 55 – Sample isosurface diagrams: plan and isometric view.

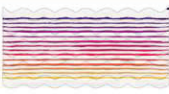
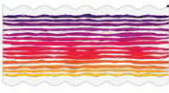
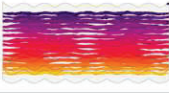
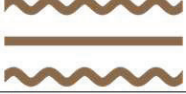
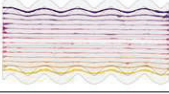
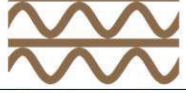
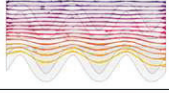
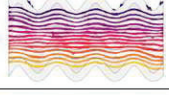
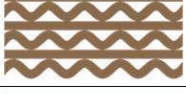
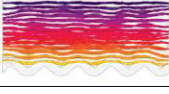
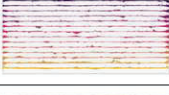
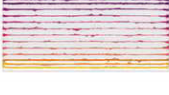
3.5. NUMERICAL RESULTS

3.5.1. U-VALUES

Table 12 below presents the simulated U-values for each geometry, as computed using the TRmesh/TRfem workflow. In addition to the U-value results, each iteration includes the following details: (1) an isosurface diagram showing the heat transfer within the geometry; (2) the thermal conductivity assigned to the earth material; and (3) the thermal conductivity assigned to air, calculated as described in Section 3.4.4.

Table 12 - U-values of the simulated geometric iterations.

Geometric iteration	Image	Isosurface diagram	Air void conductivity (W/(mK))	Earth conductivity (W/(mK))	TRfem thermal resistance (m ² K/W)	Total thermal resistance with Rse & Rsi (m ² K/W)	U-value/ Thermal transmittance (W/(m ² K))
7A-3			0.822	0.92	0.55	0.72	1.39
7A-4			0.471	0.92	0.64	0.81	1.24
7A-5			0.283	0.92	0.66	0.83	1.20
7B-3			0.722	0.92	0.62	0.79	1.26
7B-4			0.722	0.92	0.89	1.06	0.95
7B-5			0.167	0.92	0.79	0.96	1.04
7C-3			0.586	0.92	0.44	0.61	1.65
7C-3A			0.722	0.92	0.63	0.80	1.25
7C-4			0.434	0.92	0.63	0.80	1.25
7C-5			0.213	0.92	0.71	0.88	1.14
5A-4			0.563	0.92	0.63	0.80	1.25
5A-5			0.315	0.92	0.83	1.00	1.00
5A-6			0.23	0.92	0.86	1.03	0.98

Geometric iteration	Image	Isosurface diagram	Air void conductivity (W/(mK))	Earth conductivity (W/(mK))	TRfem thermal resistance (m ² K/W)	Total thermal resistance with Rse & Rsi (m ² K/W)	U-value/ Thermal transmittance (W/(m ² K))
5B-4			0.444	0.92	0.88	1.05	0.96
5B-5			0.278	0.92	1.05	1.22	0.82
5B-6			0.167	0.92	0.92	1.09	0.91
5C-3A			0.833	0.92	0.51	0.68	1.47
5C-4			0.599	0.92	0.61	0.78	1.28
5C-5			0.362	0.92	0.73	0.90	1.11
5C-6			0.224	0.92	0.77	0.94	1.07
Ref_1 (Solid Wall)			N/A	0.92	0.51	0.68	1.46
Ref_2 (Cavity Wall)			1.83	0.92	0.32	0.49	2.05

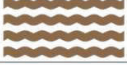
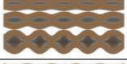
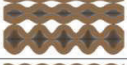
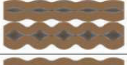
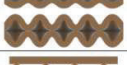
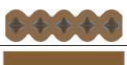
Using these U-values, the geometries were ranked from lowest (most insulative) to highest (least insulative) in Table 13. The resulting U-values ranged from 0.82 W/(m²K) to 1.65 W/(m²K). It is important to note that the thermal conductivity of the earth material, taken as 0.92 W/(mK), was a significant determinant of the U-value outcomes. Compared to other studies in the literature review, for instance, other 3D-printed earthen mixes had lower conductivity values of 0.30 to 0.50 W/(mK) [104], which could lead to lower U-values.

The following observations were made on the results:

- The majority of the lowest U-values (0.82 to 1.26 W/(m²K)) were exhibited by the B geometry across both 7 cm and 5 cm iterations. This can be attributed to: **(1) narrow airspaces, which limit air conductivity and reduce the potential for convection and radiation, and (2) a lack of direct thermal bridges between interior and exterior surfaces;**
- Geometries A and C yielded comparable results (1.14 to 1.65 W/(m²K) for 7 cm iterations and 0.98 to 1.47 W/(m²K) for the 5 cm iterations), both featuring internal touch points that allow thermal bridging, despite geometry A having closed voids;

- In general, 5 cm geometries outperformed 7 cm geometries from 2% to 21%. This advantage is due to their capacity for higher complexity (i.e. more layers and finer void subdivisions) as well as a reduced cross-sectional area of the earth material layer, resulting in increased heat resistance. However, several exceptions were observed. For instance, 7B-4, the best-performing 7 cm geometry, outperformed several complex 5 cm geometries. This could be due to the greater void depths resulting from the smaller layer thickness in geometries like 5B-4, which leads to a higher effective air conductivity. Additionally, 5A-6 and 5A-5, while more complex and subdivided, contain numerous touch points that act as thermal bridges, which 7B-4 does not have. These results suggest that **eliminating thermal bridges can have a greater positive impact on thermal performance than increasing the number of internal subdivisions or instances of branching.**
- **More complex geometries with smaller, more numerous voids tend to exhibit lower U-values than simpler ones with fewer, larger cavities.** There is an observed general improvement in performance with increasing complexity, from 3-layer to 6-layer geometries. These findings are consistent with those reported by [9, 71, 104]. Nevertheless, not all results align with this trend. B-type geometries with the highest number of layers resulted in higher U-values than their intermediate counterparts, potentially due to having overly narrow airspaces. For example, 5B-5 outperformed 5B-6, and 7B-4 outperformed 7B-5. In both cases, the isosurface diagrams revealed that too closely spaced earth layers might allow for effective heat conduction across air gaps, acting as unintended thermal bridges. To illustrate, the width of the gaps in the iterations were as follows: 5 cm (5B-5) vs 3 cm (5B-6); and 6 cm (7B-4) vs 3 cm (7B-5). These results suggest a **potential threshold air gap size**, beyond which narrowing the void ceases to improve, and may even reduce thermal performance. This observation contradicts findings by Marais et al. [90], who reported that narrower and more numerous voids improve insulation. However, the study of Briels *et al.* [9] also established a certain threshold to cell diameter (7 cm), which when further reduced offered no further improvement to performance. Therefore, experimental validation is recommended to confirm if this behavior is a result of geometry.
- Interestingly, several geometries with intermediate complexity, such as those with four layers in the 7 cm series and five layers in the 5 cm series, achieved U-values comparable to, or even better than, their more complex counterparts. These geometries also require less material, shorter print paths, and reduced print time, presenting more balanced options between performance and practicality.

Table 13 - Ranking of iterations based on U-value.

Rank	Geometric iteration	Image	U-value (W/(m ² K))
1	5B-5		0.82
2	5B-6		0.91
3	7B-4		0.95
4	5B-4		0.96
5	5A-6		0.98
6	5A-5		1.00
7	7B-5		1.04
8	5C-6		1.07
9	5C-5		1.11
10	7C-5		1.14
11	7A-5		1.20
12	7A-4		1.24
13	5A-4		1.25
14	7C-4		1.25
15	7C-3A		1.25
16	7B-3		1.26
17	5C-4		1.28
18	7A-3		1.39
19	Ref. 1 (Solid Wall)		1.46
20	5C-3A		1.47
21	7C-3		1.65
22	Ref. 2 (Cavity Wall)		2.05

- **Among the 20 iterations, U-values ranged from 0.82 W/(m²K) (5B-5) to 1.65 W/(m²K) (7C-3), and this variation can be attributed entirely to geometry. Geometry 7C-3 performed worst due to: (1) reduced wall depth resulting from inward-curving exterior and interior surfaces; (2) multiple touch points acting as direct thermal bridges between interior and exterior; and (3) limited internal subdivisions, resulting in large air voids with high conductivity. It is important to compare this with 7C-3A, which also has three layers but avoids direct thermal bridges. As a result, it significantly outperforms 7C-3 despite comparable complexity, with a U-value reduction of 24%.**

- **The two reference geometries exhibited some of the highest U-values, with the cavity wall reaching 2.05 W/(m²K) due to its large central void, which increased convection and radiation, resulting in the highest air conductivity among all tested geometries. In contrast, the best-performing geometry (5B-5) reduced the U-value of the cavity wall by 60% and that of the solid earth wall by 44%, highlighting the significant impact of geometric optimization on thermal performance.**

Figure 56 shows the simulated U-values compared against U-value standards from various European regions, in dotted lines:

- Most geometries meet the Maltese standards of 1.57 W/(m²K).
- While none comply with the Spanish Zone Alpha standard of 0.80 W/(m²K), several come very close. Notably, the best-performing geometry (5B-5) reaches 0.82 W/(m²K), only 2.5% above the target, indicating that minor design or material adjustments could achieve compliance.
- None of the geometries meet the standard for external walls of new residential buildings in Batalha, Portugal (a potential application site for this study). The best result (5B-5) still exceeds the required U-value (0.40 W/(m²K)), showing the need for significant improvement or complementary strategies to reach compliance.

As a result of these analyses, **5B-5** was selected for further optimization due to its superior thermal performance.

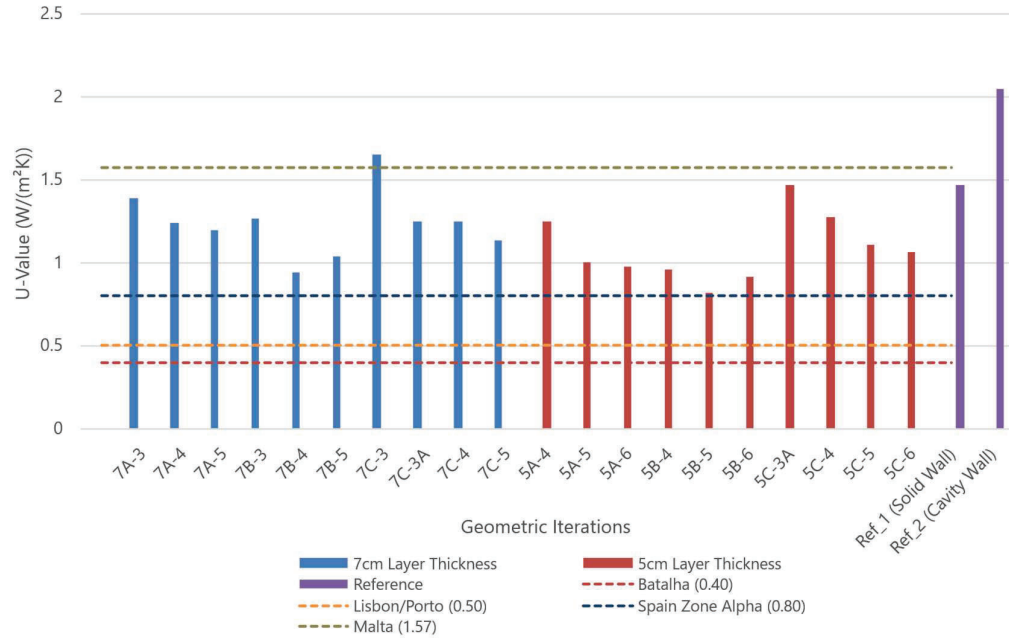


Figure 56 - Bar graph showing U-values of all analyzed geometries vs. standards.

3.5.2. THERMAL OPTIMIZATION

3.5.2.1. Optimization strategies

To address non-compliance with the U-value standards discussed, the geometry with the lowest U-value in the initial set, 5B-5, was selected for further optimization. A step-by-step framework (Figure 57) was developed to explore incremental performance improvements through the following measures:

1. Modification of print material properties – The first approach focused on improving the thermal conductivity of the 3D-printed material. Reducing this value decreases heat transfer through the solid portions of the wall, improving overall thermal performance. This approach was prioritized because it prevents the need for additional materials, either internal or external, and eliminates additional manual labor after printing. Maintaining the automated process of 3DP as much as possible is needed to preserve its productivity and economic benefits.
2. Cavity insulation or external surface treatment – If modifying the material thermal conductivity alone was insufficient to meet U-value targets, a second measure was considered: introducing cavity insulation or applying a low-conductivity external surface treatment (e.g., plaster or screed). Cavity insulation was prioritized in this study due to its higher availability and usage.
3. Combination of 1 and 2 – If adding insulation alone was not sufficient to meet targets, then both modified material thermal conductivity and insulation were jointly applied.
4. Adjustment of wall thickness or geometric complexity – If the first two measures proved insufficient, further optimization would involve altering the geometry itself, either by increasing wall thickness or changing its level of complexity. This step was not implemented within this stage but remains a future possibility.

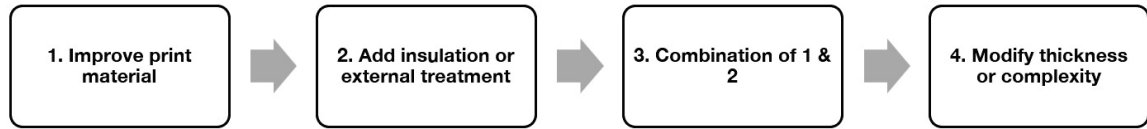


Figure 57 - Step-by-step optimization framework.

The following data and assumptions were used for the first two strategies:

1. Print material properties

- Two research articles on the thermal conductivity of 3D-printed earth materials were used as references. Both studies investigated earth mixes similar to the one used in the current simulations, containing natural fibers;
- The referenced mixes also incorporated stabilizers, particularly biopolymers, to improve various properties of the mixes, most notably compressive strength. While the primary focus was on lowering thermal conductivity, the inclusion of stabilizers was considered acceptable since these may also benefit mechanical performance in future studies;
- To isolate the effect of thermal conductivity, it was the only parameter modified from the original print material. All other variables, such as density, cost, and embodied carbon, were kept constant for consistency of comparison;
- From these references, two conductivity values were selected for sensitivity analysis: 0.37 W/(m·K) (intermediate) and 0.12 W/(m·K) (low);
- Detailed properties of the two alternative mixes are summarized in Table 14 below.

Table 14 - Summary of properties for low thermal conductivity 3DPE mixes.

	Carcassi <i>et al.</i> [40]	Rückrich <i>et al.</i> [56]
Thermal conductivity	• 0.12 W/(mK) - light straw clay (with 13 wt% fiber content) • 0.18 W/(mK) – light kenaf clay • 0.20 W/(mK) – light banana clay • 0.45 W/(mK) – light hemp clay	• 0.37 W/(mK) – printed mixture (55 vol% fibers, 1486 kg/m³ density)
Print material composition	Light fiber clay: • Natural fiber up to 13% wt or 49% volume • Biopolymers – 5% wt	• 55% fibers (oyster mushroom substrate as straw fiber) • 20% coarse sand • 25% Moza clay • 19% water
Biopolymers	Methyl cellulose, sodium alginate, locust bean gum, guar gum, and xanthan gum (all from natural sources)	Natural biopolymers (unspecified)

2. Cavity insulation

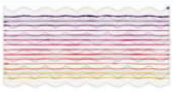
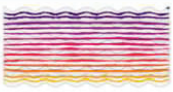
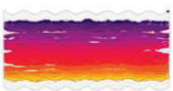
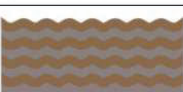
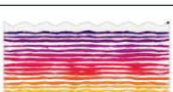
- Expanded cork granules were selected as the insulation material for its following characteristics [105]:
 - Natural and recyclable;
 - Excellent thermal and acoustic properties;
 - Suitable for application in irregularly shaped cavities;
 - High durability;
 - Widely used in Portugal.
- The thermal conductivity and density values were based on the expanded cork granule product from Amorim Cork Solutions [105], as below:
 - Density: 60-70 kg/m³;
 - Thermal conductivity: 0.041 W/(mK).

3.5.2.2. Optimized solutions

Based on the optimization strategies outlined previously, five optimized variants of geometry 5B-5 were developed. The simulation results for these variants are summarized in Table 15 and Figure 58 below. These variants allow for comparative assessment of thermal performance improvements achievable through material changes, insulation strategies, or their combination.

1. 5B-5 with low λ earth 1 (0.37 W/(m·K))
2. 5B-5 with low λ earth 2 (0.12 W/(m·K))
3. 5B-5 + cork
4. 5B-5 with low λ earth 1 + cork
5. 5B-5 with low λ earth 2 + cork

Table 15 - Optimized U-value results.

Geometric iteration	Image	Isosurface diagram	Air void conductivity (W/(mK))	Earth conductivity (W/(mK))	TRfem thermal resistance (m ² K/W)	Total thermal resistance with Rse & Rsi (m ² K/W)	U-value/ Thermal transmittance (W/(m ² K))
5B-5 Low λ Earth 1			0.278	0.37	1.51	1.68	0.60
5B-5 Low λ Earth 2			0.278	0.12	2.26	2.43	0.41
5B-5 + Cork			0.041 (Cork)	0.92	2.80	2.97	0.34
5B-5 Low λ Earth 1 + Cork			0.041 (Cork)	0.37	4.51	4.68	0.21
5B-5 Low λ Earth 2 + Cork			0.041 (Cork)	0.12	7.51	7.68	0.13

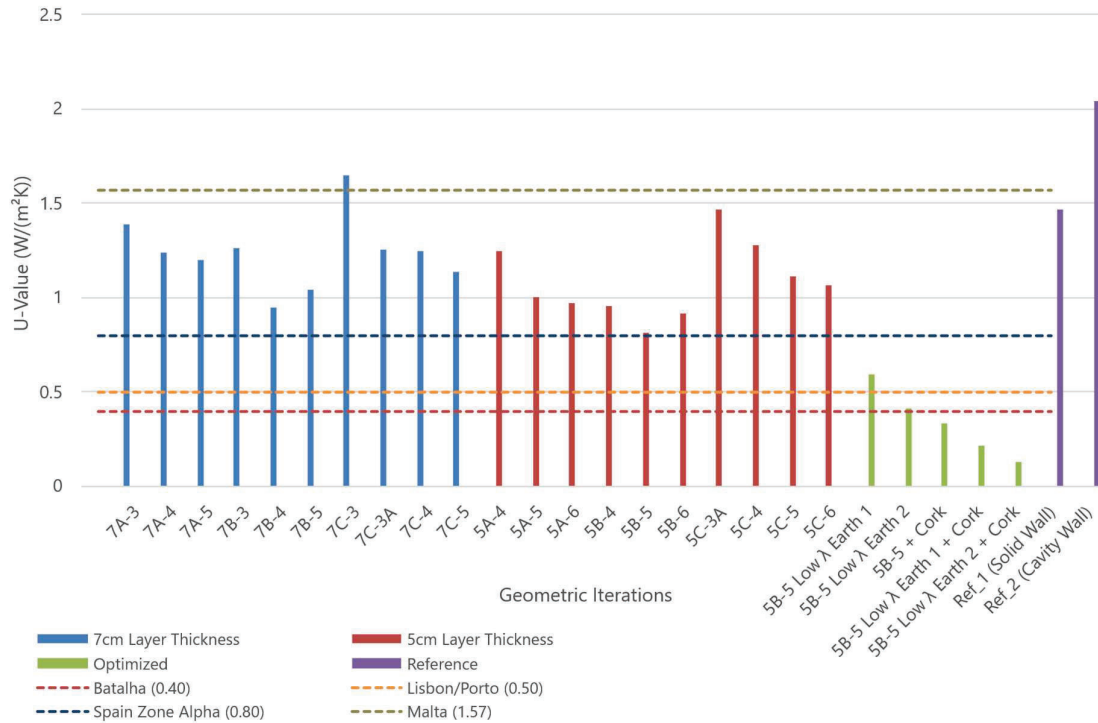


Figure 58 - Bar graph of optimized solutions U-Value results.

Based on Table 15, a progressive decrease in U-value resulted from every succeeding option. From the original 5B-5 (0.82 W/(m²K)), the following improvement was seen in each optimized option:

1. 5B-5 low λ earth 1: 27% improvement
2. 5B-5 low λ earth 2: 50% improvement
3. 5B-5 + cork: 56% improvement
4. 5B-5 low λ earth 1 + cork: 74% improvement
5. 5B-5 low λ earth 2 + cork: 84% improvement

Compared to the Portuguese U-value standard for external walls of new residential buildings in Batalha (0.40 W/(m²K)) [106], three of the five variants fully comply, while one (5B-5 low λ earth 2) exceeds the standard by only 2.5%. This demonstrates that simply improving the thermal conductivity of the print material can already lead to substantial gains in thermal performance, often requiring only minimal additional measures depending on the conductivity.

When comparing the first and second measures, results indicate that they can yield similar levels of improvement (50% for low λ earth 2 vs. 56% for cork insulation). However, as previously discussed, improving the print material is preferable because it prevents dependency on additional materials and manual processes during printing.

The most significant improvements are observed when both measures are applied together. The combined strategy, particularly in the case of 5B-5 low λ earth 2 + cork, achieves a U-value of 0.13 W/(m²K), which is 94% lower than the U-value of the reference cavity wall. This result highlights the potential of combining geometric design with material optimization to improve thermal performance in 3D-printed earth construction.

3.5.3. HOLISTIC EVALUATION

3.5.3.1. Methodology

While thermal performance is the primary focus of this study, it was considered important to include additional evaluation criteria in order to develop a more comprehensive understanding of each iteration's overall performance. Relying solely on U-values would not provide enough insight into the practical and environmental implications of implementing these wall systems in real-world contexts. As such, a holistic evaluation was carried out based on the following three dimensions (Figure 59):

- Thermal performance - Evaluated through U-values obtained from simulation.
- Sustainability - Assessed through environmental impact indicators, particularly embodied carbon or Global Warming Potential (GWP).
- Economy - Measured by estimating the cost of the wall geometry per m².

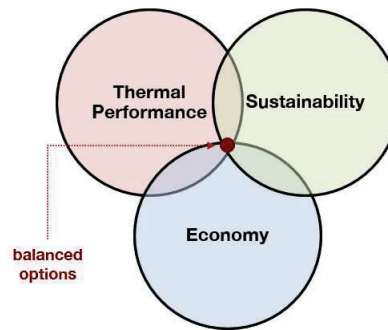


Figure 59 - The three main dimensions for holistic evaluation.

Information on the indicators, components, and considerations of the three evaluation dimensions can be seen in Table 16 below.

Table 16 - Components of the evaluation dimensions.

Evaluation dimension	Indicator	Components	Accounts for	Dependent on
Thermal performance	U-value (W/(m ² K))	N/A	Determined by the numerical simulation	
Sustainability	Embodied Carbon or Global Warming Potential (kgCO ₂ /m ²) for A1-A3 + A5 LCA stages	Earth	The embodied carbon of the unstabilized earth material (A1-A3)	Print material volume (dependent on print path length)
		Equipment	The embodied carbon of energy and petrol consumption of the equipment during the printing process (A5)	Print material volume (dependent on print path length)
		Insulation	The embodied carbon of the cork insulation for optimized cases (A1-A3)	Volume of airspaces

Economy	Cost (€/m ²)	Earth	The cost of the earth material itself	Print material volume (dependent on print path length)
		Equipment	The cost of the total energy consumption of the equipment to print 1 m ² of the wall geometry	Print time (dependent on print path length)
		Insulation	The cost of the cork insulation for optimized cases	Volume of airspaces

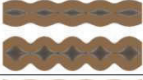
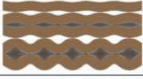
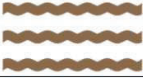
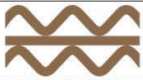
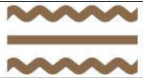
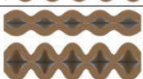
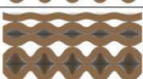
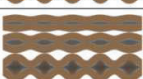
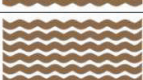
For the different components, the following values, specifications, and references were used, shown in Table 17:

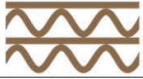
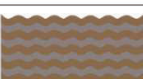
Table 17 - Values and specifications of components.

Material & equipment		Cost	Embodied carbon
Earth		25.20 €/m³ [107]	0.006 kgCO₂/kg [13]
		Includes the cost of the earth material itself	A1-A3 LCA stages; unstabilized earth
Printer system	Print time (h) * 4 kW * 0.093576 €/kWh [108, 109]		0.18 kgCO₂/kg [110]
	Includes energy consumption of gantry printer (Crane WASP), mixer, pump, etc. Figures consider Portuguese energy cost (Porto)		Includes energy and petrol consumption of gantry printer (Crane WASP), pump, mixer, sifter, IT equipment and others; A5 LCA stage
Cork		192.00 €/m³ [111]	57.30 kgCO₂/m³ [105]
	3 to 15mm granulometry; excludes VAT		A1-A3 LCA stages (excluding biogenic carbon)

To arrive at these assessments, further data were extracted from each of the 20 base geometries and the 5 optimized geometries. This included print path length, print volume, printing time, mass, and void percentage. The method of obtaining these parameters is shown in Annex A.7. All results are summarized in Table 18 below.

Table 18 - Holistic evaluation results including optimized iterations.

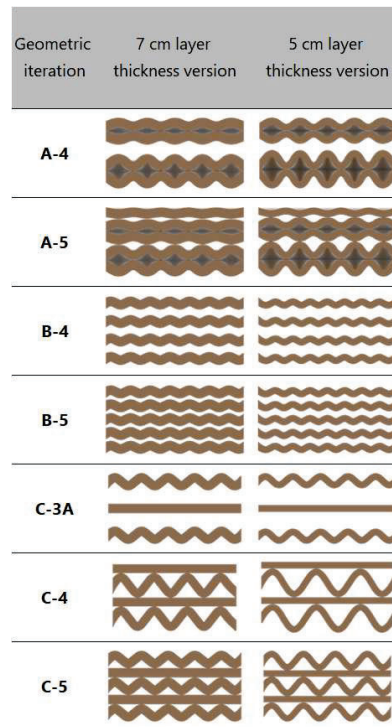
Geometric iteration	Image	U-value (W/(m ² K))	Print path length (m/m ²)	Print volume (m ³ /m ²)	Print time (hr/m ²)	Mass (kg/m ²)	Void %	Cost (€/m ²)				Embodied carbon (kgCO ₂ /m ²)			
								Earth	Equipment	Cork	Total	Earth	Equipment	Cork	Total
7A-3		1.39	119.46	0.25	0.22	448.80	50%	6.32	0.08	N/A	6.40	2.69	8.08	N/A	10.77
7A-4		1.24	150.52	0.32	0.28	565.49	35%	7.97	0.10	N/A	8.07	3.39	10.18	N/A	13.57
7A-5		1.20	183.32	0.38	0.34	688.71	23%	9.70	0.13	N/A	9.83	4.13	12.40	N/A	16.53
7B-3		1.26	120.78	0.25	0.22	453.76	53%	6.39	0.08	N/A	6.47	2.72	8.17	N/A	10.89
7B-4		0.95	156.19	0.33	0.29	586.79	37%	8.27	0.11	N/A	8.37	3.52	10.56	N/A	14.08
7B-5		1.04	191.60	0.40	0.35	719.82	21%	10.14	0.13	N/A	10.27	4.32	12.96	N/A	17.28
7C-3		1.65	130.44	0.27	0.24	490.05	35%	6.90	0.09	N/A	6.99	2.94	8.82	N/A	11.76
7C-3A		1.25	127.70	0.27	0.24	479.76	51%	6.76	0.09	N/A	6.85	2.88	8.64	N/A	11.51
7C-4		1.25	177.40	0.37	0.33	666.47	30%	9.39	0.12	N/A	9.51	4.00	12.00	N/A	16.00
7C-5		1.14	201.34	0.42	0.37	756.41	19%	10.65	0.14	N/A	10.79	4.54	13.62	N/A	18.15
5A-4		1.25	234.13	0.23	0.43	418.86	47%	5.90	0.16	N/A	6.06	2.51	7.54	N/A	10.05
5A-5		1.00	282.91	0.28	0.52	506.13	40%	7.13	0.19	N/A	7.32	3.04	9.11	N/A	12.15
5A-6		0.98	325.83	0.33	0.6	582.91	31%	8.21	0.22	N/A	8.44	3.50	10.49	N/A	13.99
5B-4		0.96	237.40	0.24	0.44	424.71	52%	5.98	0.16	N/A	6.15	2.55	7.64	N/A	10.19
5B-5		0.82	291.16	0.29	0.54	520.89	40%	7.34	0.20	N/A	7.54	3.13	9.38	N/A	12.50
5B-6		0.91	344.93	0.34	0.64	617.08	28%	8.69	0.24	N/A	8.93	3.70	11.11	N/A	14.81

Geometric iteration	Image	U-value (W/(m ² K))	Print path length (m/m ²)	Print volume (m ³ /m ²)	Print time (hr/m ²)	Mass (kg/m ²)	Void %	Cost (€/m ²)				Embodied carbon (kgCO ₂ /m ²)			
								Earth	Equipment	Cork	Total	Earth	Equipment	Cork	Total
5C-3A		1.47	190.89	0.19	0.35	341.50	63%	4.81	0.13	N/A	4.94	2.05	6.15	N/A	8.20
5C-4		1.28	268.71	0.27	0.5	480.72	47%	6.77	0.19	N/A	6.96	2.88	8.65	N/A	11.54
5C-5		1.11	320.17	0.32	0.59	572.78	36%	8.07	0.22	N/A	8.29	3.44	10.31	N/A	13.75
5C-6		1.07	350.18	0.35	0.65	626.47	28%	8.82	0.24	N/A	9.07	3.76	11.28	N/A	15.04
5B-5 Low λ Earth 1		0.60	291.16	0.29	0.54	520.89	40%	7.34	0.20	N/A	7.54	3.13	9.38	N/A	12.50
5B-5 Low λ Earth 2		0.41	291.16	0.29	0.54	520.89	40%	7.34	0.20	N/A	7.54	3.13	9.38	N/A	12.50
5B-5 + Cork		0.34	291.16	0.29	0.54	539.81	0%	7.34	0.20	34.95	42.49	3.24	9.72	10.43	23.39
5B-5 Low λ Earth 1 + Cork		0.21	291.16	0.29	0.54	539.81	0%	7.34	0.20	34.95	42.49	3.24	9.72	10.43	23.39
5B-5 Low λ Earth 2 + Cork		0.13	291.16	0.29	0.54	539.81	0%	7.34	0.20	34.95	42.49	3.24	9.72	10.43	23.39

3.5.3.2. Comparisons between iterations with different layer thicknesses

Based on the data in Table 18, a comparison was conducted between the 7 cm and 5 cm versions of the same geometric iterations. Only seven geometries exist in both versions, and all other geometries which do not have both versions were excluded from this analysis to ensure a fair, like-for-like comparison. A side-by-side image comparison is also provided below in Table 19. For a broader evaluation of all iterations, refer to Section 3.5.3.3.

Table 19 - Side-by-side comparison of 7 cm and 5 cm versions of the same geometries.



U-value

The initial hypothesis was that the 5 cm geometries would perform better thermally than their 7 cm counterparts. This expectation was based on two factors: the increased geometric complexity enabled by a smaller layer thickness, and the reduced cross-sectional area per layer, increasing resistance to heat transfer. Based on the results of Table 17, the following observations were made about the U-value in Table 20 and Figure 60:

Table 20 - U-value comparisons between 7 cm and 5 cm geometries.

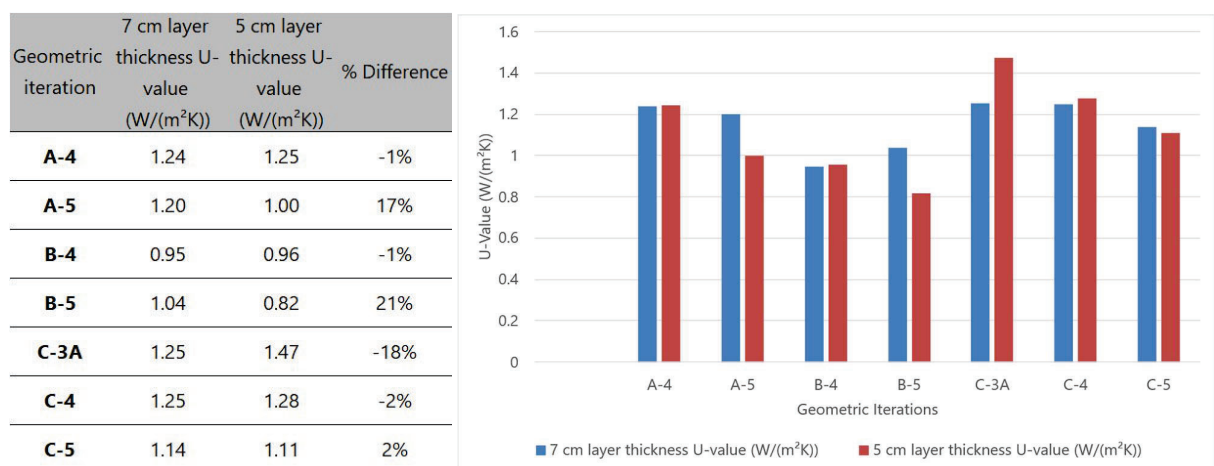


Figure 60 - U-value comparisons between 7 cm and 5 cm geometries.

- The hypothesis was confirmed in three cases, A-5, B-5, and C-5, where the 5 cm versions performed better than the 7 cm versions. However, the opposite was observed in four cases: A-4, B-4, C-3A, and C-4. While the smaller cross-sectional area in these geometries should reduce thermal bridging, the 5 cm versions exhibited higher U-values. This result can be attributed to an increase in void depth and size caused by the reduced layer thickness. In cases where no additional geometric complexity can be introduced due to the nature of the base form, decreasing the layer thickness results in larger air voids. These larger voids tend to have higher effective air conductivity, which decreases thermal performance. This effect is most clearly observed in geometry 5C-3A, where the U-value increased by 18% compared to 7C-3A.
- The overall trend indicates that when 7 cm geometries perform better than their 5 cm counterparts, the difference is marginal — typically between 1% and 2% in geometries A-4, B-4 and C-4. In contrast, when the 5 cm versions outperform the 7 cm ones, the improvements can be more significant. For example, 5B-5 outperformed 7B-5 with a 21% lower U-value, the largest improvement in the set.
- On average, the U-value decreased by 3% when comparing 5 cm to 7 cm geometries. These results highlight that **thermal performance is not determined solely by layer thickness** but by a complex interaction between void size, air conductivity, and the degree of thermal bridging through contact points. **A smaller layer thickness does not guarantee superior thermal insulation.**

Print volume

All 5 cm geometries showed a significant reduction in print volume compared to their 7 cm counterparts. This is due to the smaller cross-sectional area per layer in the 5 cm cases. The volume reductions ranged from 26% to 29%, with an average decrease of 27%. This is shown in Table 21 and Figure 61 below.

Table 21 – Print volume comparisons between 7 cm and 5 cm geometries.

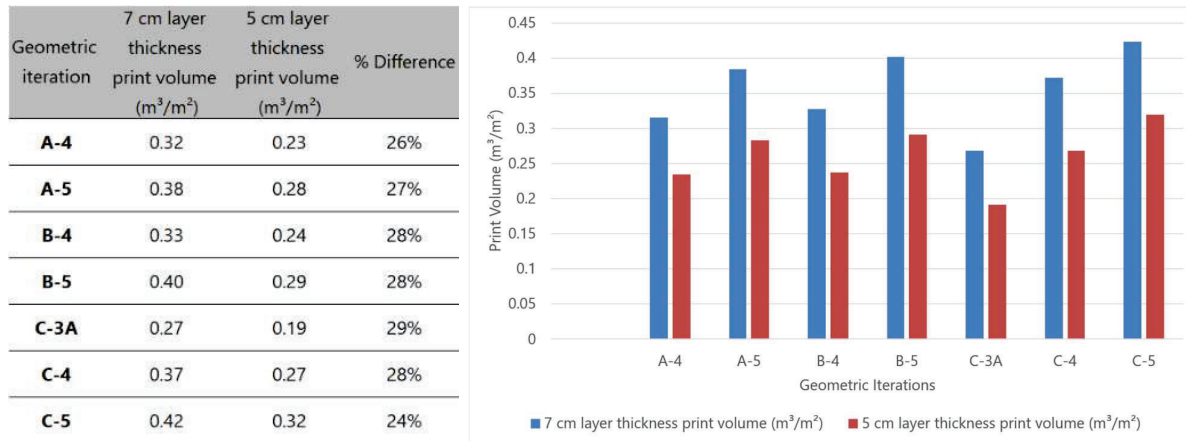


Figure 61 – Print volume comparisons between 7 cm and 5 cm geometries.

Printing time

In contrast to the reduction in volume, the **5 cm geometries required noticeably more time to print**. This is due to their smaller layer height (2 cm compared to 3 cm for the 7 cm geometries), which results in more layers for the same wall height. For instance, a 1-meter-tall wall would require 51 layers in the 5 cm version (taking C-5 0.59 hr to print), versus only 34 layers in the 7 cm version (which would take C-5 0.37 hr to print).

While the smaller layer height contributes to higher print resolution, it also significantly increases print time. The increase in printing time for the 5 cm geometries compared to the 7 cm ones ranged from 46% to 59%, with an average increase of 53%. A summary of the comparison is shown below in Table 22 and Figure 62.

Table 22 – Print time comparisons between 7 cm and 5 cm geometries.

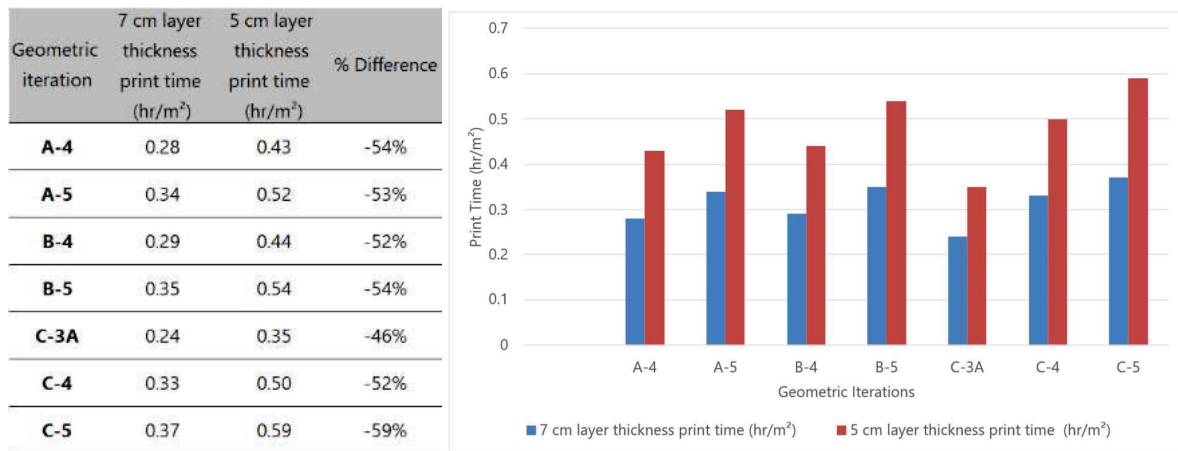


Figure 62 – Print time comparisons between 7 cm and 5 cm geometries.

Cost

Despite the longer printing time, the **5 cm geometries demonstrated a substantial reduction in cost**, with an average decrease of 26% across the seven compared iterations. This is primarily due to the reduction in earth volume required. Given that the cost of the earth material constitutes most of the total cost, this difference translates into lower overall expenses. The energy cost associated with the longer printing time is minimal in comparison and does not have a substantial impact on total cost. Table 23 and Figure 63 show these comparisons.

Table 23 – Cost comparisons between 7 cm and 5 cm geometries.

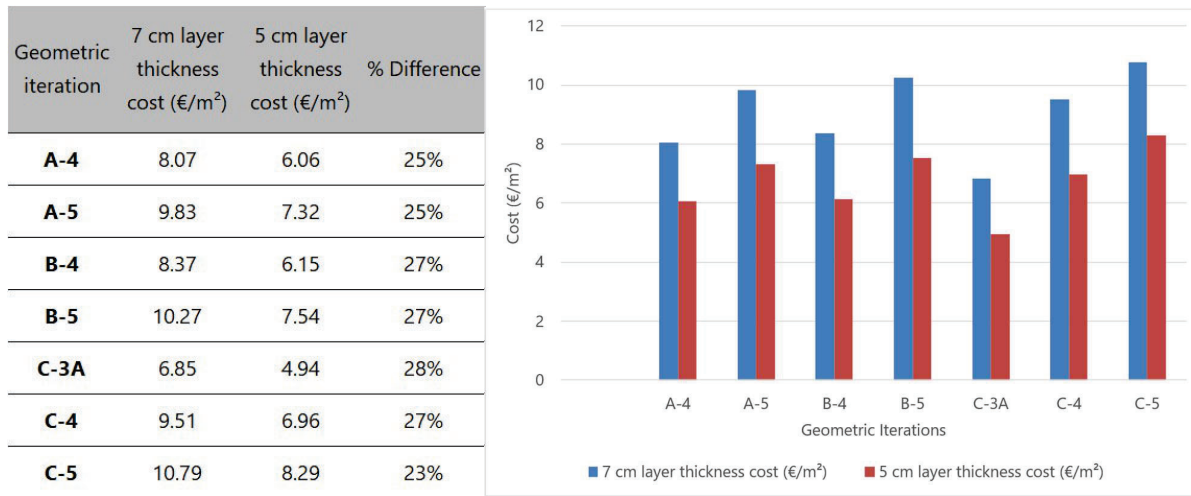


Figure 63 – Cost comparisons between 7 cm and 5 cm geometries.

3.5.3.3. Comparisons among all geometries

U-value vs. void percentage

As shown in Figure 64, there is no strong correlation between U-value and void percentage across all geometric iterations. This supports findings from the state-of-the-art review, which emphasized that thermal performance is more strongly influenced by the size, shape, and distribution or number of voids, rather than by void percentage alone.

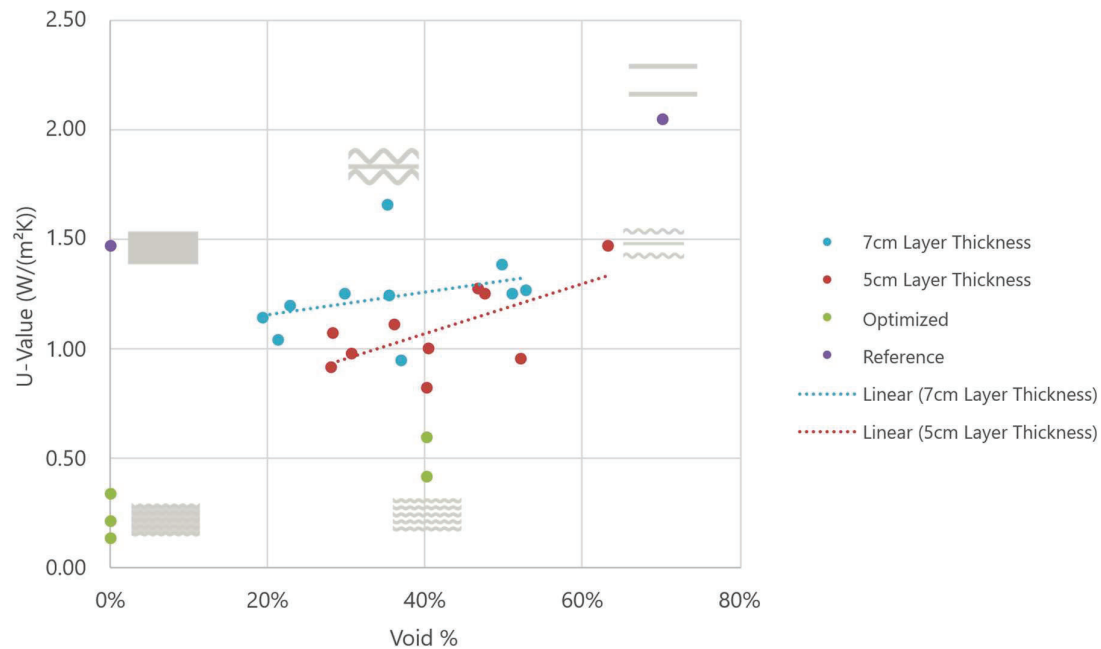


Figure 64 – Void percentage vs U-value.

Using void percentage as a single metric for predicting thermal behavior may be insufficient. A void percentage of 50%, for example, could be achieved in multiple ways: either by having one half of the wall as a monolithic solid and the other half as a single air cavity, or by using a highly complex structure composed of finely distributed void regions. Despite sharing the same void percentage, these two configurations would result in significantly different thermal performances.

This observation aligns with the findings of Cuevas et al. [10], who concluded that there is no direct relationship between solid content (and therefore air void percentage) and thermal conductivity. This effect is especially apparent in the central cluster of data points on the graph, where geometries with void percentages ranging from 20% to 50% exhibit comparable U-values. Additionally, as discussed in Section 3.5.3.2, the 5 cm geometries generally show lower U-values than their 7 cm counterparts, despite having similar void percentages.

Nevertheless, when observing the trendlines on the graph, both for the 7 cm and 5 cm series, a slight positive slope can be seen. This suggests that higher void percentages are loosely associated with higher U-values. Although the correlation is weak, it supports the general conclusion presented in the study by Marais *et al.* [90] and Chamatete and Yalçinkaya [11], which discussed that lower void percentages tend to correlate with lower U-values.

From this, it can be concluded that there is a **weak inverse correlation between void percentage and thermal performance**. However, it is important to emphasize that **thermal performance also depends heavily on the size, shape, and distribution or number of the voids** within the wall.

This is particularly evident when examining the two reference geometries. The cavity wall, which contains a single large undivided void with a void percentage of 70%, exhibits the highest U-value among all geometries. This is due to the high air conductivity within the large void. In contrast, the solid earth wall reference, which has 0% voids, performs better thermally despite relying entirely on the conductivity properties of the earth material.

Print volume vs. U-value

Figure 65 illustrates the relationship between print volume and U-value, providing a general overview of thermal performance in relation to sustainability and cost. In this case, print volume was chosen as a proxy metric as it can encapsulate most of the factors that influence both embodied carbon and cost.

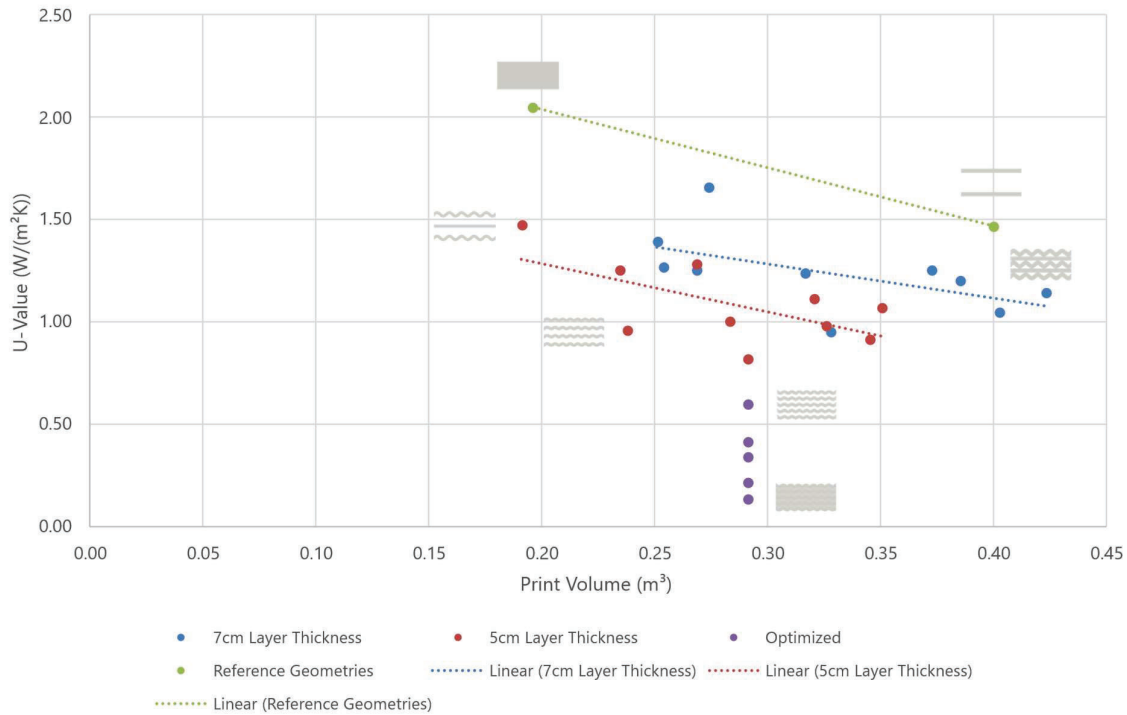


Figure 65 – Print volume vs U-value.

For the unoptimized cases, there is a general trend where – comparing **within the same layer thickness** – **higher U-values are associated with lower print volumes**, and lower U-values with higher print volumes. This trend is expected within iterations of the same layer thickness, as increased material usage often enables the formation of more intricate geometries. Such geometries are typically capable of incorporating strategies identified in the state-of-the-art, including enhanced thermal mass, increased number of air voids, thermal lag, intermediate barriers, and functional exterior shapes, all of which contribute to improved thermal performance. This relationship is reflected in the trendlines for each series (7 cm, 5 cm, and reference geometries), all of which exhibit negative slopes. The implication is that **increasing print volume generally leads to better thermal performance, provided the geometry works to introduce strategies that improve performance**.

This observation is consistent with the findings of Curth et al. [14], who noted that introducing more material into the inner structure of their bricks by adding internal air pockets increased the time constant (an indicator that encompasses thermal conductivity). However, this improvement in performance comes at the expense of increased embodied impact.

However, it is important to highlight that print volume alone does not determine thermal performance, and the way the print material is organized within the geometry plays a more critical role. For example, if a large print volume is concentrated in a solid mass without internal subdivision, as in the solid earth reference wall, then thermal performance may not improve despite the higher print volume.

The **5 cm geometries tend to show both lower U-values and lower print volumes** when compared to the 7 cm geometries, suggesting a more efficient use of material in achieving thermal performance. Across all cases, print volume ranges from 0.19 m³ (5C-3A) to 0.42 m³ (7C-5).

Excluding the optimized iterations, the most favorable cases (i.e. those with both low U-value and low print volume) can be said to include iterations of 5A (5A-5) and 5B (5B-4, and 5B-5), just visually basing

on the graph. On the other hand, the geometries with the highest U-values and print volumes can be said to be 7A-5, 7C-4, and 7C-5. However, a more quantitative assessment is required to rank these geometries objectively, and is addressed in Section 3.5.4.

The unoptimized geometries with the highest and lowest U-values were compared against the two reference geometries to gain additional insight into the effect of geometry on the print volume and U-value metrics. The summary of the comparison is shown in Table 24 below. Positive effects are in green, while negative effects are in red.

Table 24 – Comparison between reference geometries and best and worst unoptimized cases.

Unoptimized cases	Reference 1: solid earth wall		Reference 2: cavity wall	
	Print volume	U-value	Print volume	U-value
Lowest U-value (5B-5)	↓ 28%	↓ 44%	↑ 45%	↓ 60%
Highest U-value (7C-3)	↓ 33%	↑ 13%	↑ 35%	↓ 20%

Against Reference 1 (the solid earth wall): 5B-5, which has the lowest U-value among the unoptimized cases, reduces print volume by 28% and U-value by 44%. In contrast, 7C-3, which has the highest U-value in the unoptimized cases, reduces print volume by 33% but increases the U-value by 13%. When comparing against Reference 2 (the cavity wall): 5B-5 increases print volume by 45%, but reduces the U-value by 60%. 7C-3 on the other hand, increases print volume by 35% and reduces the U-value by 20%.

The optimized geometries generally fall near the average range of print volumes for both the 7 cm and 5 cm series. However, their U-values are among the lowest in the set, reflecting the effectiveness of the optimization strategies applied. As previously noted, three of these optimized geometries already meet the performance criteria set by the U-value standard for new residential buildings in Batalha, Portugal.

3.5.3.4. Beyond thermal performance: cost and embodied carbon

Cost

Beyond thermal performance, the data in Table 18 provides insights into the economic and environmental implications of the various geometries through their associated costs and embodied carbon.

Figure 66 below shows a summary of the cost of each iteration, as well as its subcomponents. It can be observed that the **primary contributor to cost in the 20 unoptimized geometries is the earth material**. On average, earth makes up approximately 98% of the total cost in geometries without cork insulation. It is important to note that if the soil is sourced directly from the site (if deemed suitable for use), then only the labor cost for extraction would comprise the cost of earth.

In contrast, equipment cost, comprised of energy consumption during the printing process, is minimal, contributing only around 2% of the total cost in cases without cork. The energy requirement, although higher for finer resolution prints such as the 5 cm geometries, has a small impact on total cost due to its relatively low weight in the total cost.

Cork insulation has the highest cost among the components analyzed. In the optimized geometries that include cork, it accounts for an average of 82% of the total cost. Consequently, the three optimized geometries that incorporate cork insulation have the highest costs, reaching €42.49 per square meter of wall. In contrast, the geometry with the lowest cost is 5C-3A, with a cost of €4.94 per square meter. This is attributed to its minimal print volume, which directly reduces costs.

As previously discussed, **7 cm geometries generally tend to be costlier than their 5 cm counterparts**, primarily due to their larger print volumes. Since earth is the dominant factor in total cost, any increase in volume translates proportionally into cost. As mentioned, although 5 cm geometries require longer print times due to smaller layer heights, the increase in energy use does not significantly impact total cost.

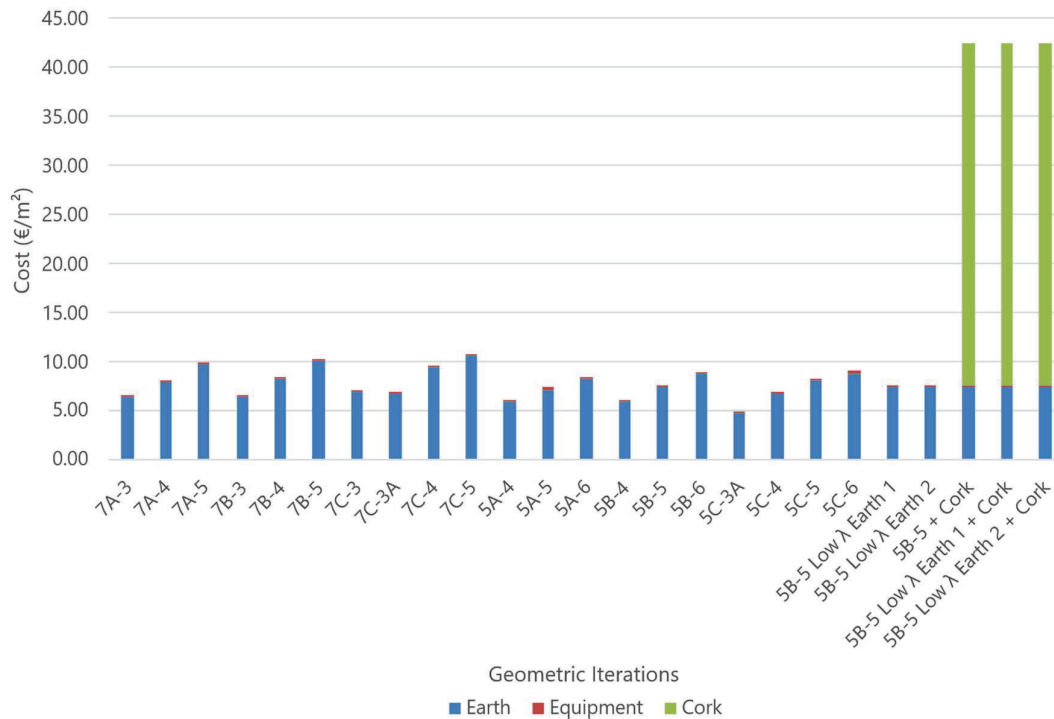


Figure 66 – Cost for all analyzed geometric iterations.

Correlation between U-value and cost

When plotting U-value against cost (Figure 67 below), an inverse correlation can be observed. This means that **lower U-values are generally associated with higher costs**. This trend is particularly evident when observing the optimized geometries with cork insulation, which achieve the lowest U-values but incur the highest costs. Conversely, geometries with higher U-values tend to have lower costs, especially those without cork. This inverse relationship is also reflected in the trendlines across each geometry series (7 cm, 5 cm, and optimized cases), all of which exhibit negative slopes.

Notably, the **5 cm geometries often achieve both lower U-values and lower costs** when compared to the 7 cm geometries, which suggests a more economic approach to thermal performance. For the unoptimized geometries, the inverse relationship between cost and U-value can be attributed to higher volumes and print times, associated with better performing geometries (as shown in Figure 65 - Print Volume vs U-value). Higher-performing geometries tend to have greater complexity and volume, which increases material usage and, therefore, cost.

For the optimized geometries, the sharp increase in cost alongside the decrease in U-value is primarily due to the introduction of cork insulation. While this material significantly enhances thermal resistance, its high cost has a substantial impact on overall expenses.

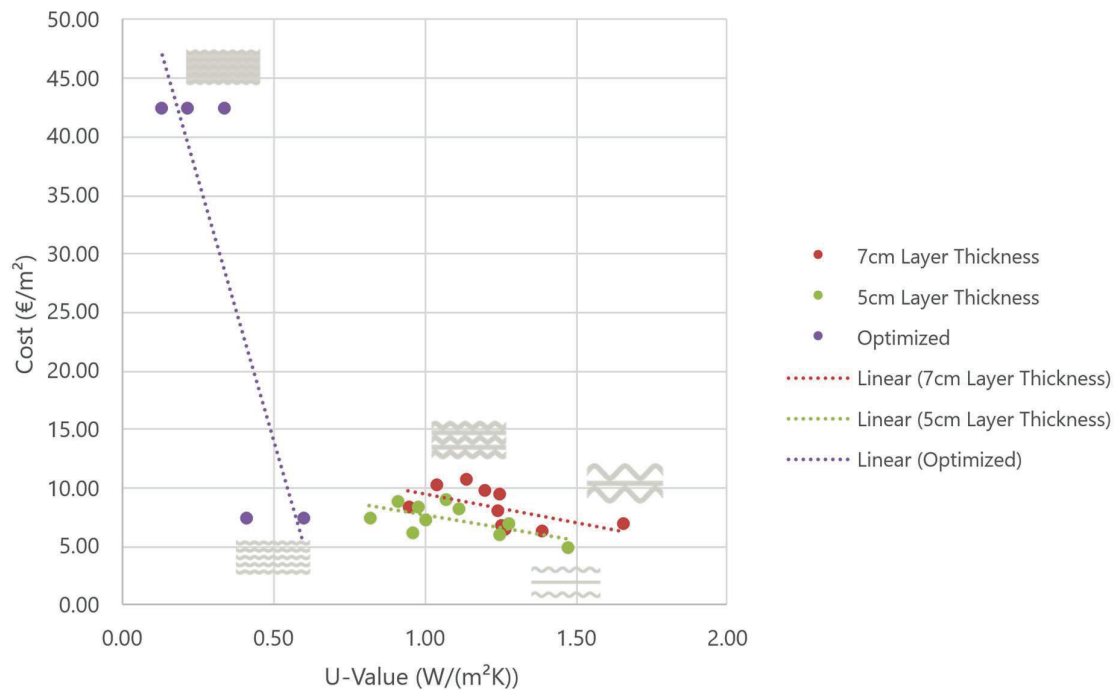


Figure 67 – U-value vs cost.

Embodied carbon

In analyzing embodied carbon (Figure 68 below), it was found that **for all iterations without cork, the equipment used in the printing process is the primary contributor**. On average, equipment accounts for 75% of the total embodied carbon per geometry. This includes both energy and petrol consumption during the operation of the printing system. In contrast, earth material contributes the smallest portion, averaging just 25% of the total embodied carbon in each geometry.

Due to the addition of cork insulation, the last three optimized cases with cork have the highest embodied carbon. In these cases, cork contributes 45% of the total, while equipment accounts for 42%. It is important to note, however, that this analysis takes into account only GWP of fossil fuels and does not account for biogenic carbon, which would bring the net embodied carbon of cork to negative values and make the comparison disproportionate for the system boundaries of A1-A3 + A5.

As observed with cost, the **5 cm geometries generally exhibit lower embodied carbon than the 7 cm ones**. This is primarily a result of their smaller print volumes, which reduce material usage and therefore environmental impacts. Among all iterations, 5C-3A exhibits the lowest embodied carbon at 8.20 kgCO₂/m². This represents a 65% reduction compared to the optimized cork-insulated cases and highlights that material-efficient designs have environmental advantages.

It is also important to clarify that the earth material used in the optimized cases was assumed to have the same embodied carbon as the base earth material in the 20 unoptimized geometries, despite having lower thermal conductivities. This assumption does not account for the potential embodied carbon increase from added biopolymers or additives used to enhance performance. Future studies may refine this analysis by incorporating the carbon impact of such incorporations.

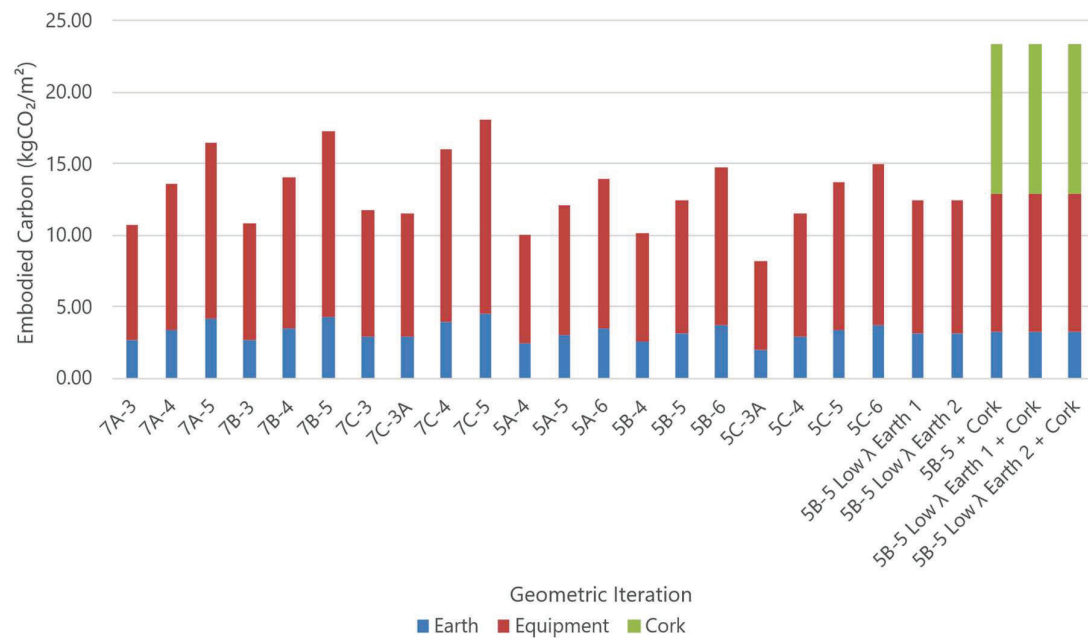


Figure 68 – Embodied carbon for all analyzed geometries.

U-value vs embodied carbon

Based on Figure 69 below, a clear inverse correlation can be observed when plotting U-value against embodied carbon, similar to the relationship between U-value and cost. Geometries with **lower U-values tend to exhibit higher embodied carbon**, while those with higher U-values correspond to lower embodied carbon. This relationship is expected, given that embodied carbon is directly proportional to print volume, and print volume is inversely related to U-value, as previously shown in Figure 65 (Print volume vs U-value).

This trend is also supported by the negative slopes of the trendlines across all geometry categories: 7 cm, 5 cm, and optimized iterations. It is also evident that the **5 cm geometries generally achieve both lower U-values and embodied carbon** compared to their 7 cm counterparts. This advantage is primarily due to their smaller print volumes, which are associated with lower material use and energy demand.

For the optimized cases, the distinct increase in embodied carbon, alongside the decrease in U-value, is also attributed to the addition of cork insulation. While cork improves thermal performance, it also contributes to the total embodied carbon of the wall. This highlights the balance required between improved performance and environmental impact in the assessment of the geometries.

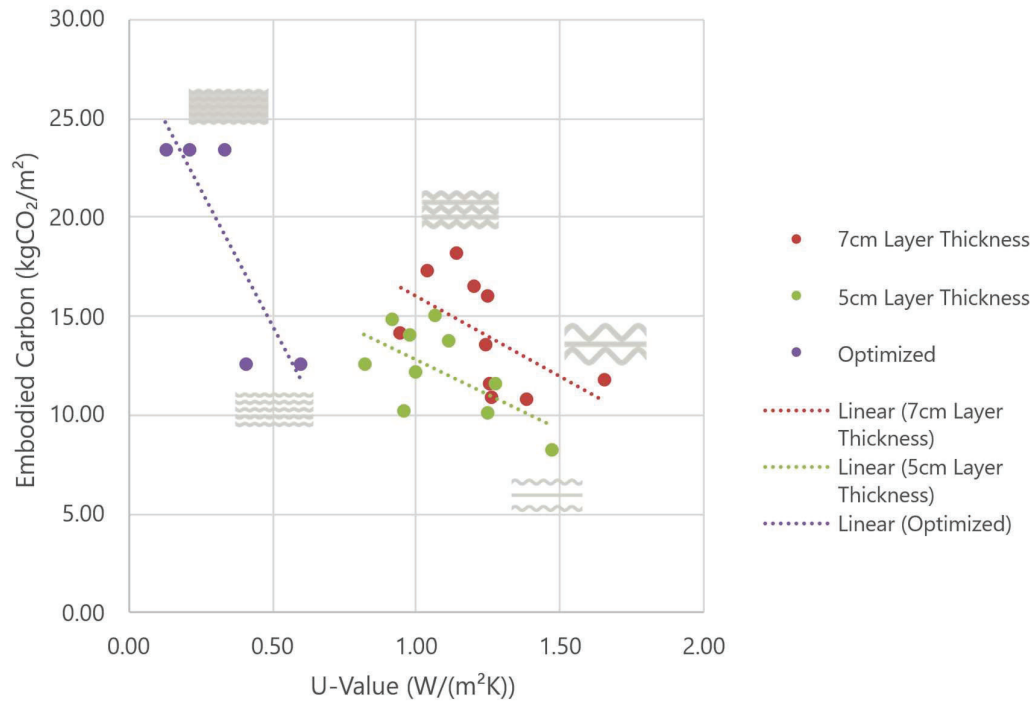


Figure 69 – U-value vs embodied carbon.

3.5.4. OVERALL BEST PERFORMERS

Following the analyses above, the MARS-SC method was used to quantitatively identify the best overall performing geometries. MARS-SC is a method for the comparative assessment of different solutions, proposed by Ricardo Mateus from The University of Minho [112].

It first involved the normalization of indicators by determining a value for the performance level of each indicator on a dimensionless scale from 0 (worst solution) to 1 (best solution). The normalized value for the indicator i for a certain solution, was obtained through formula (3):

Where I_i is the value of the indicator i for that solution; I_{ip} is the value of the indicator i , for the worst solution; and I_{im} is the value of the indicator i , for the best solution.

$$\bar{I}_i = \frac{I_i - I_{ip}}{I_{im} - I_{ip}} \quad (3)$$

Afterwards, weighting and aggregation were performed. Aggregation in this case was done to determine the global assessment score of each geometric iteration, across the dimensions of thermal performance, sustainability, and economy. A weighting system was then used. In this study, two weight scenarios were used, depending on potential needs or desired priorities:

1. Equal weights for the three dimensions:
 - **U-value:** 33.3%
 - **Cost:** 33.3%
 - **Embodied carbon:** 33.3%

2. Priority on thermal performance:

- **U-value:** 50%
- **Cost:** 25%
- **Embodied carbon:** 25%

The aggregated assessment score of a specific solution is then given by formula (4):

Where NS is the sustainability level of the solution; n is the number of considered indicators; P_i is the weight assigned to the indicator i; and $\bar{I}_i$ is the normalized value of the indicator i, for the solution [0-1].

$$NS = \sum_{i=1}^n P_i \times \bar{I}_i \quad (4)$$

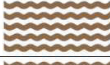
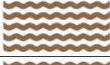
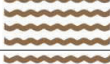
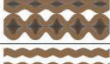
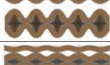
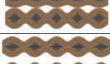
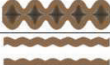
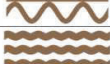
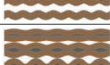
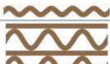
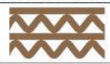
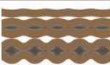
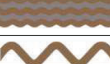
Following this procedure, the MARS-SC results are shown in Table 25 below:

Table 25 – MARS-SC method normalization and aggregation.

Geometric Iteration	Original			Normalized			Aggregated assessment scores	
	U-Value (W/(m ² K))	Cost (€/m ²)	Embodied carbon (kgCO ₂ /m ²)	U-Value (W/(m ² K))	Cost (€/m ²)	Embodied carbon (kgCO ₂ /m ²)	Aggregated assessment score (Equal weights)	Aggregated assessment score (U/C/E: 50/25/25)
7A-3	1.39	6.40	10.77	0.17	0.96	0.83	0.66	0.54
7A-4	1.24	8.07	13.57	0.27	0.92	0.65	0.61	0.53
7A-5	1.20	9.83	16.53	0.30	0.87	0.45	0.54	0.48
7B-3	1.26	6.47	10.89	0.25	0.96	0.82	0.68	0.57
7B-4	0.95	8.37	14.08	0.46	0.91	0.61	0.66	0.61
7B-5	1.04	10.27	17.28	0.40	0.86	0.40	0.55	0.52
7C-3	1.65	6.99	11.76	0.00	0.95	0.77	0.57	0.43
7C-3A	1.25	6.85	11.51	0.26	0.95	0.78	0.66	0.56
7C-4	1.25	9.51	16.00	0.27	0.88	0.49	0.54	0.47
7C-5	1.14	10.79	18.15	0.34	0.84	0.34	0.51	0.47
5A-4	1.25	6.06	10.05	0.27	0.97	0.88	0.70	0.60
5A-5	1.00	7.32	12.15	0.43	0.94	0.74	0.70	0.63
5A-6	0.98	8.44	13.99	0.44	0.91	0.62	0.66	0.60
5B-4	0.96	6.15	10.19	0.46	0.97	0.87	0.76	0.69
5B-5	0.82	7.54	12.50	0.55	0.93	0.72	0.73	0.69
5B-6	0.91	8.93	14.81	0.49	0.89	0.56	0.65	0.61
5C-3A	1.47	4.94	8.20	0.12	1.00	1.00	0.71	0.56
5C-4	1.28	6.96	11.54	0.25	0.95	0.78	0.66	0.55
5C-5	1.11	8.29	13.75	0.36	0.91	0.63	0.63	0.56
5C-6	1.07	9.07	15.04	0.38	0.89	0.55	0.61	0.55
5B-5 Low λ Earth 1	0.60	7.54	12.50	0.69	0.93	0.72	0.78	0.76
5B-5 Low λ Earth 2	0.41	7.54	12.50	0.82	0.93	0.72	0.82	0.82
5B-5 + Cork	0.34	42.49	23.39	0.86	0.00	0.00	0.29	0.43
5B-5 Low λ Earth 1 + Cork	0.21	42.49	23.39	0.95	0.00	0.00	0.32	0.47
5B-5 Low λ Earth 2 + Cork	0.13	42.49	23.39	1.00	0.00	0.00	0.33	0.50

Given the aggregated assessment scores for the two weighting scenarios, two ranking lists were created (as shown below in Table 26) to identify the overall best performing iterations in both weighting scenarios. The following observations were made regarding the resulting ranking lists:

Table 26 – Ranking lists for the geometric iterations.

Rank	Geometric iteration	Image	Aggregated score (equal weights)	Rank	Geometric iteration	Image	Aggregated score (U/C/E: 50/25/25)
1	5B-5 Low λ Earth 2		0.82	1	5B-5 Low λ Earth 2		0.82
2	5B-5 Low λ Earth 1		0.78	2	5B-5 Low λ Earth 1		0.76
3	5B-4		0.76	3	5B-4		0.69
4	5B-5		0.73	4	5B-5		0.69
5	5C-3A		0.71	5	5A-5		0.63
6	5A-4		0.70	6	7B-4		0.61
7	5A-5		0.70	7	5B-6		0.61
8	7B-3		0.68	8	5A-6		0.60
9	7C-3A		0.66	9	5A-4		0.60
10	7A-3		0.66	10	7B-3		0.57
11	5C-4		0.66	11	5C-5		0.56
12	7B-4		0.66	12	7C-3A		0.56
13	5A-6		0.66	13	5C-3A		0.56
14	5B-6		0.65	14	5C-4		0.55
15	5C-5		0.63	15	5C-6		0.55
16	7A-4		0.61	16	7A-3		0.54
17	5C-6		0.61	17	7A-4		0.53
18	7C-3		0.57	18	7B-5		0.52
19	7B-5		0.55	19	5B-5 Low λ Earth 2 + Cork		0.50
20	7C-4		0.54	20	7A-5		0.48
21	7A-5		0.54	21	7C-4		0.47
22	7C-5		0.51	22	5B-5 Low λ Earth 1 + Cork		0.47
23	5B-5 Low λ Earth 2 + Cork		0.33	23	7C-5		0.47
24	5B-5 Low λ Earth 1 + Cork		0.32	24	5B-5 + Cork		0.43
25	5B-5 + Cork		0.29	25	7C-3		0.43

- The top four performing geometries were consistent across both ranking scenarios. All four belonged to the **B geometry group with a 5 cm layer thickness**. Among them, the optimized geometry **5B-5 using low-conductivity earth 2 was identified as the overall best performer**.
- The two highest-ranked geometries for both rankings were optimized versions that used only low-conductivity earth. In contrast, the **three optimized cases that included cork insulation ranked significantly lower** due to their high cost and embodied carbon. In the equal-weight scenario, these cork-insulated cases were positioned at the bottom of the list.
- In general, **5 cm geometries were ranked higher than 7 cm geometries** across both ranking scenarios. However, some exceptions were observed. For example, 7B-4 performed better than many 5 cm geometries in the 50-25-25 ranking, due to its simple form that resulted in a relatively low print volume despite its 7 cm layer thickness. Combined with its strong thermal performance (the third lowest U-value among unoptimized cases), it achieved a high assessment score.
- Geometries with **highly complex forms and void subdivisions**, particularly the C variants, **consistently ranked in the lower half**. This outcome may be attributed to their high print volumes and print times, which resulted in higher embodied carbon and cost – factors that were not sufficiently compensated by their improved thermal performance. The results emphasize the importance of a holistic assessment, as even geometries that perform best thermally may rank poorly overall if their cost and environmental impact are not proportionally justified. In some cases, geometries with only moderate thermal performance achieved better rankings by minimizing material use and resource consumption.
- Ultimately, it can be seen that, **depending on the weighting system used, the ranking results may vary greatly**. As such, it is important to determine the primary goals and priorities of the project, i.e. whether the aim is to maximize thermal performance, minimize embodied carbon, or reduce cost, in order to arrive at the most appropriate recommendations for the project.

3.6. 3D PRINTING PROTOTYPES

3.6.1. METHODOLOGY

The scaled 3DP of three specific geometries was carried out. The most complex iterations from each base geometry (at 7 cm layer thickness) were selected to assess buildability. A WASP 40100 printer was used, with clay serving as a representative material for earth due to its workability, availability, and printability. In addition to serving as a proof of concept, the printed prototypes provide initial insights into buildability and can potentially be used for future experimental validation. This would support comparisons between the physical performance of the geometries and the accuracy of the numerical simulations. The printing process included the following steps:

1. Scaling down the parametric models, based on nozzle size
 - a. As one of the available nozzle diameters was 8 mm, it was decided to create a scaled layer thickness of 10 mm, which equates to a 1:7 scale. This creates a wall section that is 20 cm wide x 20 cm tall.
2. Contouring of the scaled model according to the scaled layer height
 - a. While the actual 1:1 layer height is to be 3 cm, a 2.5 mm layer height was deemed appropriate to avoid printing issues given the 8 mm nozzle.
3. Dispatching, flipping, and weaving of contours (Figure 70)
 - a. The direction of every other contour was flipped, so that the printer nozzle begins the succeeding layer at the top of the point where the previous layer ended. This is to reduce travel time and, therefore, the overall printing time.

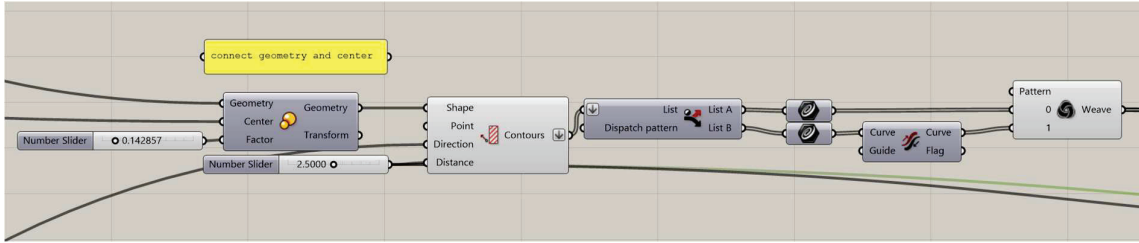


Figure 70 – Dispatch, flip, and weave components.

4. G-code generation using the Termite plugin (Figure 71)
 - a. Termite is a slicer plugin for Grasshopper developed for LDM 3D printers with nozzle sizes ranging from 1 to 8 mm, such as the WASP 40100 LDM. It allows the designing of printing paths using Rhinoceros, Grasshopper or Termite components while exporting all necessary data as g-code in real-time (Figure 72), ready to be executed [113]. The plugin also gives information on print volume and estimated printing time.

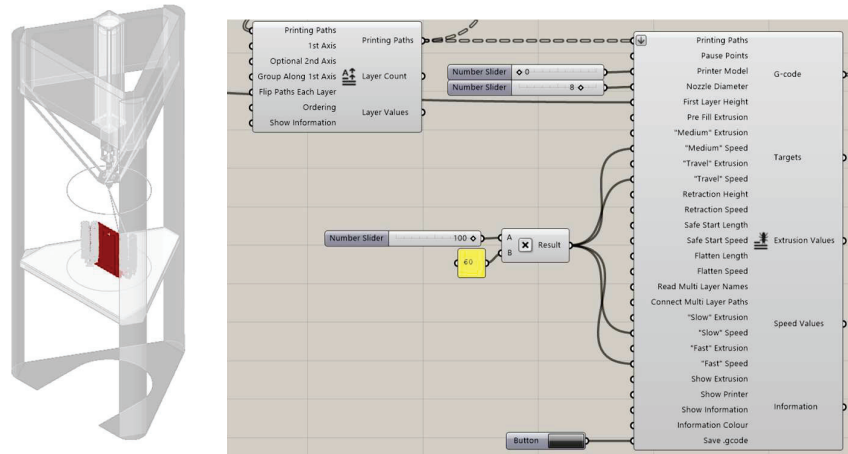


Figure 71 – Termite plugin with inputs (printing speed used: 100 mm/s).

```

0 ; Generated by Termite 1.1 (Build 300125) by Julian Jauk IAM TU Graz
1 ; Termite built with Grasshopper 1.0.0007
2 ; Saved with Rhino Version: 8.17.25066.7001
3 ; Saved on OS: Microsoft Windows NT 10.0.26100.0
4 ; Saved by User: felic
5 ; Saved at: .. :
6 ; Estimated Printing Time: 00:14:50 (hh:mm:ss)
7 ; Printing Path Length: 88782 mm
8 ; Estimated Material Consumption: 3196.152 cm³ (8 mm Nozzle)
9 ; Printer Model: Delta WASP 40100 Half
10 ; Layer "Slow" Speed: 6000 Extrusion: 1 Paths: 0
11 ; Layer "Default" Speed: 6000 Extrusion: 1 Paths: 80
12 ; Layer "Fast" Speed: 6000 Extrusion: 1 Paths: 0
13 ; Layer "Travel" Speed: 6000 Extrusion: 0 Paths: 0
14 ; Pause Points: 0
15 ; Read Multi Layer Names: False
16 ; Connect Multi Layer Paths: False
17 ; First Layer Height: 2.5 mm
18 ; Pre Fill: 2 mm
19 ; Safe Start Speed: 1500 mm/m Length: 8 mm
20 ; Flatten Speed: 1500 mm/m Length: 4 mm
21 ; Retraction Speed: 1500 mm/m Height: 2 mm
22 M117 Termite Homing ;
23 G28 ; MOVE TO ORIGIN (HOME)
24 G21 ; UNITS: MM
25 G90 ; ABSOLUTE COOD
26 M82 ; ABSOLUTE EXTRUDE
27 M117 Termite Printing ;
28 ; END OF HEADER
29 G92 E0 F0 ;
30 G0 X100 Y26.79 Z4.5 E0 F6000 ; END OF TRAVEL
31 G1 X100 Y26.79 Z2.5 E2 F1500 ; END OF RETRACT DOWN
32 G1 X97.44 Y27.63 Z2.5 E4.7 F1500
33 G1 X92.52 Y29.61 Z2.5 E10 F1500 ; END OF SAFE START
34 G1 X92.31 Y29.72 Z2.5 E10.24 F6000
35 G1 X91.03 Y30.19 Z2.5 E11.6 F6000
  
```

Figure 72 – Excerpt of a sample g-code.

5. Testing of the g-code on CAMotics
 - a. CAMotics is an open-source simulator for 3-axis g-code programs, allowing for the visualization of results in 3D [114].
 - b. Before physical printing, the generated g-code was tested using Camotics software for initial checks and error detection, mitigating potential issues.
6. Preparation of printing material
 - a. The print material used was a SiO₂ PA white earthenware body (clay).
 - b. The material was mixed with water and kneaded to create a homogeneous, extrudable mixture.
7. Calibration of the printer (WASP 40100)
 - a. Auto-homing the printer
 - b. Modifying the z-max settings to the height of the printing platform
 - c. Ensuring a consistent air pressure of 0.7 MPa for material extrusion
 - d. Extruding a small amount of material until no air gaps were visible in the hose, ensuring a smooth and continuous flow
8. 3D printing
 - a. During the actual 3DP process, the printability of the sample and the print properties (e.g., printing time, speed, and flow) were assessed and recorded. Adjustments to speed and flow were made in case of inconsistencies in the print. Material reparation and reprinting were performed for any printing failures (e.g. the mixture was too viscous, leading to geometric irregularities).
9. Drying and baking
 - a. Following the 3DP process, the samples are left to air dry for 3 to 5 days. A visual inspection was then performed to check for cracks, deformities, or shrinkage.
 - b. To remove the samples from the green state (unfired, moldable state of a clay body) and to make them more durable and usable for future experimental validation, the prints were then baked with the following settings and heating rates used for kiln firing:
 - i. Up to 100 °C: 10 °C/h (evaporation of residual moisture)
 - ii. From 100 °C to 600 °C: 50 °C/h (removal of chemically bound water and organic burnout)
 - iii. Above 600 °C to 1080 °C: 60 °C/h (final densification)
 - iv. Soak time: Hold at peak temperature for approximately 15–30 minutes, adjusted according to wall thickness and kiln load, to ensure uniform heat distribution.

3.6.2. RESULTS

To assess buildability, the most complex iterations of each 7 cm geometry were 3D-printed using clay at 1:7 scale, 20 cm wide x 20 cm tall. The results of the prints are shown below in Figure 73. *Geometry A was prepared for printing but, due to printer malfunction, could not be printed at the time of submission. For completeness, this geometry is presented in Figure 73 using its digital model.*

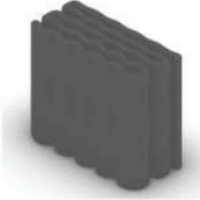
	Geometry A	Geometry B	Geometry C
Print speed	Not printed due to printer malfunction at the time of submission	50%	100%
Print flow		112%	32%
Printing time		25 min.	27 min.
Isometric view			
Top view			
Side view			

Figure 73 – 3D printing parameters and results.

Differences in print speed and flow were caused by minor inconsistencies in the clay mixture. At times, the material was too viscous, producing a wider layer thickness than intended. In such cases, adjustments were made by reducing the print speed or flow to maintain the integrity of the design. For instance:

- Geometry B is designed such that layers do not touch, intentionally creating narrow air gaps for improved thermal performance. To achieve this, both speed and flow were adjusted, resulting to the ideal configuration of 50% of the programmed speed and 112% of the programmed flow. The slower speed reduced instability during extrusion, especially since the design lacks internal supports on the shorter axis of the wall. The increased flow then compensated for the reduced speed to maintain the desired layer thickness.
- Geometry C requires precise contact between the wave and straight layers at tangential points. This required fine-tuning of the print parameters to ensure layers were neither too thin nor too thick. The optimal setting for this geometry was found to be 100% of the programmed print speed and 32% of the programmed flow.

Buildability assessment

- Geometry C exhibited excellent buildability, showing no major issues during printing. The presence of internal contact points along the wave layers provided lateral support similar to a truss system. This feature helped maintain layer alignment and reduced deflection during printing.
- In contrast, geometry B experienced buildability challenges. Due to the absence of internal contact points, the geometry lacked lateral support, especially on the shorter axis. Despite using the optimized print settings mentioned above, the layers showed an increasing degree of instability and deviance from the print path as height increased (which resulted to accumulated weight). In the finished model, this behavior is clearly visible at the midpoint and at the top.
- This issue is consistent with observations from earth-printing trials, such as in the EcoMIT project (Figure 74), where a wall without internal infill collapsed at the eighth layer, particularly along longer wall spans.
- One potential solution is the introduction of intermediate connectors within the wall, as employed in projects by Havelar. These connectors act as bracing elements to improve structural stability during and after printing. While steel connectors are often used in practice, alternative low-conductivity materials such as plastics or timber could be explored to minimize thermal bridging. Another option is to optimize the print material itself, to make it more stable immediately after deposition. This can be done by incorporating a superplasticizer, for instance. However, the use of these interventions would impact thermal performance, cost, and embodied carbon, and so would need to be carefully evaluated.
- If buildability is treated as a primary consideration and given that the best-performing B geometries present buildability concerns without additional support measures, the next best-ranked geometries with integrated contact or support points could be considered. In this case, the A geometry could be a suitable candidate (provided it shows sufficient structural stability during printing, with its cantilevers).



Figure 74 – Wall collapse of 3D-printed earth at the eighth layer of printing at long wall spans (left and center) (Courtesy: EcoMIT Project); Intermediate connectors (right) (Courtesy: Havelar).

It is apparent in the models that the exterior profiles of both the B and C geometries introduce surface undulations that have the potential to influence thermal performance. As seen in the printed samples, these wavy surfaces can create localized shading, as indicated by the visible shadows in the photos.

According to the literature review, such surface geometries can either increase or decrease shading or exposure to solar radiation, thereby affecting thermal gain or loss. The amplitude and frequency of these exterior waves can be calibrated to suit specific climatic contexts and orientations, potentially enhancing passive thermal performance. For example, deeper surface profiles may offer greater shading in hot climates, while smoother surfaces may be more suitable in colder regions.

3.7 CONCLUSIONS

This chapter outlines a research approach that investigates the thermal performance of 3D-printed wall geometries. The study was based on a comprehensive state-of-the-art review to identify key factors influencing thermal behavior in 3D-printed structures, which informed the conceptualization of novel base geometries. These geometries were then parametrically modeled in Rhino/Grasshopper, enabling the creation of numerous iterations with varying complexity for sensitivity analysis. Numerical simulations, utilizing steady-state 3D heat transfer analysis with TRfem, were used to quantify thermal transmittance (U-value) while balancing it against practical factors like print path length, print time, cost, and embodied carbon. Subsequently, selected geometries were 3D-printed at scale to assess buildability and printability. The collected simulation and practical data were analyzed comparatively, with embodied carbon and cost figures derived from literature and market data, all contributing to final conclusions and future recommendations.

The results highlight that the absence of thermal bridges, along with void subdivision and compartmentalization, plays a critical role in reducing heat transfer. While several geometries improved performance through these mechanisms, most did not meet stringent U-value standards. However, particular geometries came close (e.g. 5B-5, which reached $0.82 \text{ W/(m}^2\text{K)}$, only 2.5% above the Spanish Zone Alpha standard of $0.80 \text{ W/(m}^2\text{K)}$), demonstrating that geometry alone can significantly influence thermal performance. By performing optimization on the best-performing geometry, performance was further improved, with three designs achieving compliance with Portugal's Batalha U-value standard for external walls of new residential buildings ($0.40 \text{ W/(m}^2\text{K)}$). These improvements were achieved either through changing earth material conductivity or adding cork insulation.

A holistic evaluation using the MARS-SC method considered the dimensions of thermal performance, cost, and embodied carbon, using two weighting scenarios. The best overall performers were 5 cm B-type geometries, particularly those with reduced conductivity but no added insulation. While cork-insulated cases performed best thermally, they ranked lower overall due to high cost and embodied carbon. Trends across the parameters showed inverse relationships between U-value and cost and embodied carbon, meaning better thermal performance typically comes at the expense of higher resource use. Cost analysis showed earth as the dominant cost driver, while embodied carbon was driven mostly by equipment use. In both cases, 5 cm geometries were generally more efficient due to their smaller volumes. Ultimately, only a project's goals and priorities will determine the most appropriate geometry for its needs.

3DP trials revealed buildability challenges, specifically with geometry B, which faced stability issues from its unsupported design. This highlights that printability must also be considered alongside performance.

In summary, the study shows that geometric design alone can have a significant impact on improving thermal performance, and that sustainable, high-performing 3DPE walls are achievable.

4

CONCLUSIONS

4.1. SUMMARY OF THE STUDY

This study investigated the thermal performance of 3DPE wall geometries, aiming to identify designs that achieve an optimal balance between thermal performance (quantified by U-value) and practical considerations such as cost, and sustainability metrics such as embodied carbon. Recognizing the significant environmental impact of the construction industry and the emerging potential of 3DPE as a sustainable and low-carbon alternative, the research aimed to address existing gaps in understanding the thermal behavior of complex 3DPE wall structures and their ability to meet stringent energy efficiency standards.

The methodological approach involved a detailed state-of-the-art review to establish geometric concepts that can improve thermal performance, followed by the conceptualization and parametric modeling of novel base wall geometries. These geometries were then systematically iterated into various complexity levels and two different layer thicknesses (7 cm and 5 cm) to facilitate a sensitivity analysis. Numerical simulations, specifically steady-state 3D heat transfer analysis using TRmesh and TRfem plugins within Rhino/Grasshopper, were employed to quantify the U-value of each iteration. Additionally, selected geometries underwent scaled 3DP with clay to gain initial insights into their buildability.

The study's findings revealed that specific geometric iterations, particularly those from geometry B, consistently exhibited the lowest U-values primarily due to their narrow airspaces and the absence of direct thermal bridges, and that 5 cm geometries generally outperformed their 7 cm counterparts. While initial designs often did not meet stricter European U-value standards, such as those of Portugal, further optimization of the best-performing geometry (5B-5) through modifying earth material conductivity and/or incorporating cork insulation significantly improved thermal performance. This enabled three variants to achieve compliance with the strict U-value standards of Batalha, Portugal for new residential buildings' external walls.

A holistic evaluation, incorporating cost and embodied carbon considerations with thermal performance, highlighted an inverse relationship where better thermal performance often came with higher costs and embodied carbon. Ultimately, the multi-criteria assessment using the MARS-SC method and two weighting scenarios identified optimized 5B-5 with a low-conductivity earth material as the overall best performer, demonstrating that efficient designs and material improvements can be more balanced solutions than relying solely on added insulation, which contributed significantly to cost and embodied carbon. However, it is important to note that this assessment may change depending on a project's weighted goals and priorities, which will determine the most appropriate geometry for its needs.

Finally, the 3DP tests emphasized the importance of buildability by showing that certain geometries, despite their robust thermal characteristics, may present significant construction challenges without integrated geometric support. Potential workarounds were then proposed in such cases.

4.2. RESPONSE TO THE PROBLEM STATED

This study addresses the challenges facing the construction industry, particularly its significant contribution to global energy consumption and carbon emissions, and its lagging productivity. With the need for low-carbon and energy-efficient building solutions, the research focused on 3DPE walls, which offer inherent advantages such as low embodied carbon, local material availability, and good thermal properties. By exploring geometric configurations afforded by 3DP, this research provides a strategy to enhance the thermal performance and energy efficiency of building envelopes, while at the same time addressing material efficiency, reduced waste, and design flexibility that are difficult to achieve with conventional methods. This approach aligns with the overarching goal of reducing operational energy demand and environmental impact in buildings, therefore contributing to more sustainable construction practices.

4.3. PROPOSED OBJECTIVES/ACHIEVED RESULTS

The primary goal of this study was to identify optimal 3DPE wall geometries that achieve the best balance among thermal performance, cost and embodied carbon, which both encompass print path length, print volume, and printing time. This approach aimed to provide insights into the overall performance of these components.

The following objectives were achieved:

- Optimal geometries identified - Through numerical simulations, Geometry 5B-5 was identified as the best-performing unoptimized geometry thermally, achieving a U-value of $0.82 \text{ W}/(\text{m}^2\text{K})$, significantly outperforming both the conventional cavity wall and solid earth wall references by 60% and 44% respectively.
- Thermal performance optimization demonstrated - The study demonstrated that further U-value improvements can be achieved through material property modification and additional measures, such as cavity insulation. The optimized 5B-5 variants, particularly 5B-5 low λ earth 2 + cork, achieved the lowest U-value of $0.13 \text{ W}/(\text{m}^2\text{K})$, widely surpassing the Portuguese U-value standard for the Batalha region ($0.40 \text{ W}/(\text{m}^2\text{K})$) for new residential buildings' external walls.
- Holistic multi-dimensional evaluation - Using the MARS-SC method, a holistic evaluation of geometries was conducted considering thermal performance, sustainability (embodied carbon), and economy (cost). This revealed that 5B-5 with low λ earth 2 was the overall best performer when balancing these critical aspects.
- Buildability assessment insights - Scaled 3DP of selected geometries provided initial insights into their buildability. While geometry C demonstrated excellent buildability, geometry B encountered significant stability challenges due to the absence of internal support, highlighting the need for considering constructability alongside thermal performance.

4.4. RESULTS ACHIEVED IN EACH OF THE PREVIOUS CHAPTERS

The methodology outlined in Chapter 3.1 led to the following results at each stage:

- State-of-the-art: This initial phase established a deep understanding of existing geometric strategies for enhancing thermal behavior in 3DP structures. Major geometric design principles

were synthesized, including the importance of thermal mass distribution, optimal air void characteristics (size, shape, distribution, and closed cells), thermal lag and branching, the use of multi-row configurations, and manipulation of exterior shapes for passive performance.

- Conceptualization of base geometries: Building upon the literature review, three novel base geometries (geometry A, B, and C) were conceptualized. These designs incorporated combinations, reinterpretations, or innovations of identified thermal concepts, and were chosen based on factors such as print path considerations, continuity of print path, and adaptability for creating iterations of differing complexity.
- Parametrization of base geometries: The finalized base geometries were translated into parametric models using Grasshopper within Rhinoceros, enabling systematic iteration for sensitivity analyses. Boundary constraints, such as a 40 cm wall thickness, and 7 cm or 5 cm print layer thicknesses, were consistently applied to ensure comparability.
- Iteration of base geometries: A total of 20 unoptimized and 5 optimized geometric iterations were generated. This included three complexity levels for each base geometry and two layer thicknesses (5 cm and 7 cm), allowing for a sensitivity analysis on the influence of geometric complexity on thermal performance and factors such as print path length and print volume. Manual iteration was adopted due to the limitations of direct integration with multi-objective optimization plugins.
- Numerical simulations: Steady-state 3D heat transfer analysis was conducted using the TRmesh and TRfem plugins for all 25 geometries to quantify their U-values.
 - Performance trends: Geometry B consistently showed the lowest U-values, primarily due to narrow airspaces and the absence of direct thermal bridges. While 5 cm geometries generally outperformed 7 cm ones, this was not universal, highlighting the complex interplay of void size, air conductivity, and thermal bridging. An increase in geometric complexity generally improved performance, though overly narrow air gaps in some B-type geometries led to unintended thermal bridging, suggesting a potential optimal air gap size. The worst-performing geometry (7C-3) suffered from reduced wall depth, direct thermal bridges, and limited internal subdivisions.
 - Optimization: The selected optimal geometry, 5B-5, underwent further optimization by adjusting print material conductivity and adding cork insulation. These strategies led to substantial U-value reductions, with three optimized variants successfully meeting stringent Portuguese U-value standards.
- Analysis and comparison: A multi-dimensional evaluation was performed, assessing thermal performance, cost, and embodied carbon.
 - U-value vs. void percentage: No strong correlation was found, reinforcing that void size, number, shape, and distribution are more critical than void percentage alone.
 - Print volume vs. U-value: An inverse relationship was observed for unoptimized cases, with higher print volumes (comparing within the same layer thickness) generally leading to lower U-values due to increased geometric complexity. 5 cm geometries generally achieved better performance with lower print volumes.
 - Cost analysis: The earth material was found to be the dominant cost driver in unoptimized geometries, while cork insulation significantly increased costs in optimized cases. 5 cm geometries were generally more cost-effective due to reduced material volume.
 - Embodied carbon analysis: Equipment energy and petrol consumption were the primary contributors to embodied carbon in unoptimized designs, while cork insulation substantially increased total embodied carbon in optimized cases (though biogenic carbon was not accounted for). Similar to cost, 5 cm geometries exhibited lower embodied carbon due to smaller print volumes.

- Overall ranking: For the two weighting scenarios used (equal weights and 50/25/25 U-value/Cost/Embodied Carbon), the MARS-SC method defined 5 cm B-type geometries as the top performers overall, with optimized versions using low-conductivity earth ranking highest. This highlighted that geometries with high thermal performance might rank lower holistically, if their cost and environmental impacts are disproportionately high as well.
- 3D printing: Scaled prototypes of the most complex 7 cm geometries were 3D-printed using clay. This process provided qualitative insights into the buildability of the designs. Geometry C was highly buildable due to its internal support points, whereas geometry B faced significant stability issues from its lack of internal contact points, necessitating print parameter adjustments and highlighting the need for internal connectors. The exterior wavy profiles of both geometries were observed to have potentially beneficial thermal implications through shading and radiation exposure.

4.5. CONTRIBUTION TO THE TOPIC'S BODY OF KNOWLEDGE

This research contributes to the growing body of knowledge on 3DPE structures and their thermal performance by addressing the following identified research gaps:

- Focus on 3DPE geometry and thermal performance: Unlike many studies focused on cementitious materials, this thesis provides insights into the thermal performance specifically of 3DPE wall geometries, an area with limited existing research.
- Exploration of complex geometries: The study explored a range of geometries with increasing complexity, including those with manipulations on the vertical axis, to demonstrate their quantitative impact on U-value and other factors.
- Compliance with thermal standards: This research demonstrated that complex 3DPE wall geometries can already comply with less stringent European U-value standards (e.g. in Malta) without additional measures. Further, particular geometries when optimized can meet more stringent European U-value standards (e.g., in Portugal) without relying on excessively large amounts of conventional insulation infill.
- Holistic multi-criteria evaluation: By integrating thermal performance with economic and environmental assessments (cost and embodied carbon), the study provides a more comprehensive and realistic understanding of potential trade-offs in design. This addresses the lack of studies on the "coupling relationship" between thermal and other performance aspects, showing that designs with the best thermal performance may not be the optimal choice when considering overall sustainability and cost.
- Refined methodology: The research established and validated a detailed workflow for integrating parametric design (Rhino/Grasshopper), numerical simulation (TRmesh/TRfem with custom C# for multi-material classification), and scaled physical prototyping, offering a guide or framework for future studies in this field.
- Specific geometric insights: The findings offer insights into the interplay of factors like layer thickness, void size/shape/distribution, and thermal bridging in 3DPE walls, providing observations that sometimes challenge existing literature (e.g. the potential negative impact of overly narrow airspaces, contradicting some findings).

4.6. CONSTRAINTS OF THE PROCESS

Throughout this research, certain constraints and limitations were encountered, primarily related to the simulation tools and the overall workflow:

- TRmesh/TRfem plugin limitations
 - TRmesh and TRfem were observed to be prone to crashes or errors. Meshing would fail unpredictably due to high sensitivity to mesh issues, peeling, or geometric complexity. For each geometry, several trials had to be done, often after long waiting times, to find a resolution that provides a working mesh.
 - TRmesh and TRfem possessed an arbitrary nature and lacked available information for proper utilization. Coordination with the plugin's developer was necessary to obtain the correct workflows.
 - The manual nature of baking geometries and meshing errors required by TRmesh and TRfem prevented full automation of optimization studies with plugins like Wallacei or Galapagos, requiring a manual iteration workflow.
 - TRfem's solver handles only conductive heat transfer. With this, convection and radiation within the air voids were manually incorporated into the assigned air conductivity values. Similarly, surface resistances are not modeled directly and need to be added during post-processing.
 - While TRmesh can technically be used to mesh more than one solid with different materials, constant meshing errors prevented this feature from being usable. To work around this, a custom C# script was developed to perform the classification of each tetrahedron to assign it the correct conductivity, effectively allowing the use of just a single, holistic mesh. This added complexity to the workflow and potentially took away from the accuracy of the simulation, compared to having a native feature of the plugin to recognize different materials.
 - Achieving the ideal mesh edge length (validated for accuracy) was not always possible for all complex geometries due to TRmesh limitations, leading to an expected $\pm 3\%$ discrepancy in simulation results compared to analytical calculations.
 - Despite these limitations, this method was able to provide an effective workflow for evaluating early-stage thermal performance in complex 3DP wall geometries, directly within the Rhino/Grasshopper environment.
- Assumptions and simplifications in modeling
 - Air conductivity averaging – For geometries with complex or varying void dimensions on both horizontal and vertical axes, an effective overall air conductivity was averaged and applied to all voids due to computational demands, which can potentially over- or underestimate local changes in heat transfer.
 - Embodied carbon of optimized earth mixes – The embodied carbon of optimized earth mixes was assumed to be the same as the base earth material, without accounting for the potential carbon impact of added biopolymers or bio-additives that can improve performance.
 - Steady-state analysis – The simulations focused on steady-state heat transfer, which simplifies the more dynamic and transient thermal behavior of buildings in real-world conditions. While this was deemed suitable for comparative analysis as many studies do, it does not fully capture effects that are dependent on time.
- Scaled prototyping scope – the 3DP stage involved scaled prototypes primarily for initial buildability assessment. Full experimental thermal performance validation was outside the scope of this phase, meaning numerical results for thermal performance still require experimental confirmation.

- Material inconsistencies in printing – Minor inconsistencies in the clay mixture during scaled printing required impromptu adjustments to print speed and flow, showing the sensitivity of the physical printing process.

4.7. FUTURE DEVELOPMENTS

Building upon the insights and methodologies developed in this thesis, the following recommendations for future research and development are proposed:

- Experimental validation of thermal performance – the most crucial next step is to conduct full-scale experimental validation of the selected optimal geometries through hot-box testing, for instance. This would provide empirical data to confirm the U-value results from the numerical simulations and help resolve any discrepancies observed, for example concerning the behavior of very narrow air gaps which was seen to contradict published literature. In addition, dynamic analyses may be employed to investigate beyond simplified, steady-state results and account for the effects of the exterior façade profile on shading and radiation exposure.
- Exploration of more complex geometries – the literature review shows that there is much potential in exploring more complex geometries, or geometries of a different approach, to achieve even lower U-values that could decrease additional measures needed for compliance with standards.
- Coupled performance analyses – integrate the analysis of thermal performance with other aspects, such as structural performance, to ensure buildability and structural integrity. Additionally, expanding the holistic evaluation to include moisture behavior, acoustic performance, and fire resistance would provide a more comprehensive assessment of 3DPE wall systems, moving forward the concept for real-world applications. Full-scale earth prints can also be made, to assess buildability and performance at the 1:1 scale.
- More comprehensive embodied carbon and cost analyses – wider system boundaries for the sustainability analysis, such as cradle-to-cradle, can be used for a more robust and holistic overview of the environmental impact of the wall geometries. In these cases, biogenic carbon may be considered to truly compare the amount of embodied carbon throughout the life cycle. In addition, other indicators aside from GWP may be incorporated for a more global analysis. For cost, considering other parameters such as labor and the transport of equipment would create a more accurate picture of the overall cost structure of each printed geometry.
- Automated, parametric optimization – explore more robust and automated multi- or single-objective optimization plugins (e.g., Wallacei, Galapagos), for a complete parametrization of the workflow. This can be done with TRmesh/TRfem once it can be integrated, or with other simulation tools that allow for a seamless feedback loop between geometric iteration and performance analysis. This would enable a significantly higher number of iterations that are optimized against multiple criteria, accomplished much faster compared to manual iteration.
- Climate-specific geometric calibration – develop or apply parametrization to modulate exterior wall facades (e.g., amplitude and frequency of wavy surfaces) of 3DP walls to improve passive thermal performance for specific climatic contexts. In addition, mixing and matching of wall geometries can be explored to come up with optimal solutions for specific instances or orientations. The study can be opened to different contexts as well, not just in Portugal, to investigate the optimal geometric solutions depending on regional climates. A base geometric model may be created, that can be adapted worldwide and integrate considerations on local materials, climates, and technologies, to meet regional U-value requirements.

- Refined air void thermal modeling – assigning individual thermal conductivities to differently sized or shaped air voids within a single geometry in simulations, to capture heat transfer mechanisms more accurately compared to using averaged values.
- Expanded material research
 - Conduct embodied carbon assessments for modified earth mixes with low conductivity, accounting for the life cycle impacts of all bio-additives and bio-stabilizers used to enhance thermal or mechanical properties.
 - Explore and test low-conductivity alternative materials for intermediate connectors (e.g., bio-based plastics or timber) to provide structural stability without compromising environmental impact, cost, or thermal performance through thermal bridging.
- Energy modelling of spaces and buildings – once the U-values of different wall geometries are established, energy modelling of entire rooms or buildings can be performed to quantify performance gains on a larger scale. Example plugins or software for this would be Honeybee under Ladybug, or EnergyPlus.
- Off-site production considerations – if the focus shifts to off-site printing of bricks or blocks, refine the models and simulations to reflect the shorter component lengths and the inclusion side walls, which would affect thermal bridging.
- Application to traditional construction components – the geometric principles identified in this study can be explored further for transversal application to common building components, such as masonry bricks or blocks. For instance, molds (which are used to create the common concrete hollow block) may be reshaped to incorporate more subdivided void structures, or less direct thermal bridges, to improve their passive performance. Mass production of these components may lead to a deeper, broader enhancement of passive performance achieved through geometric manipulation, increasing sustainability in today's construction market.
- Incorporation of artificial intelligence (AI) – AI may be explored for use in the workflow described, especially in the performance optimization of geometric iterations. This optimization may encompass not only thermal performance, but also cost, embodied carbon, material selection, and other metrics deemed critical.

5

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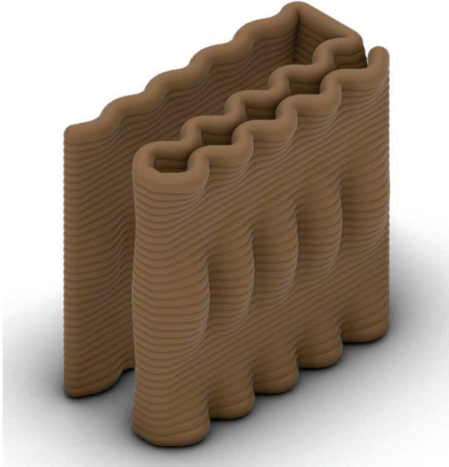
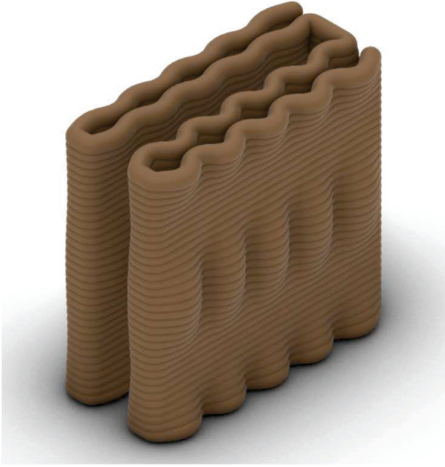
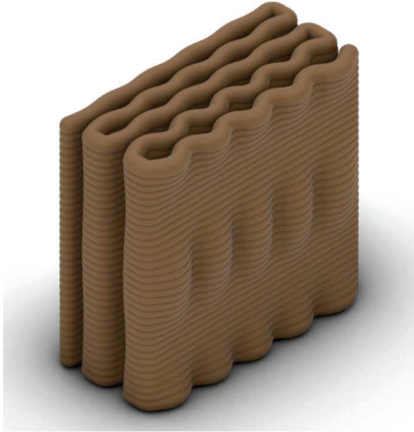
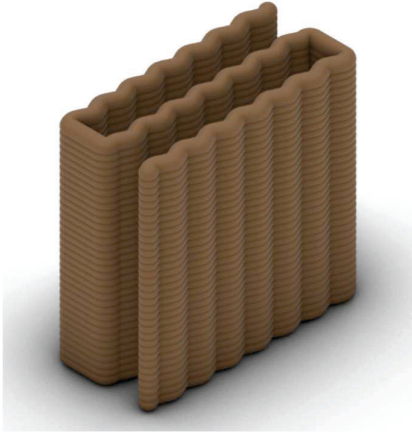
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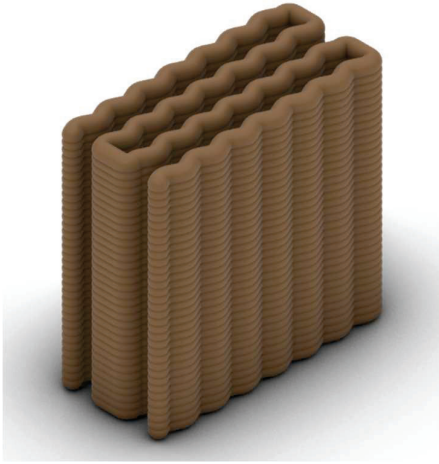
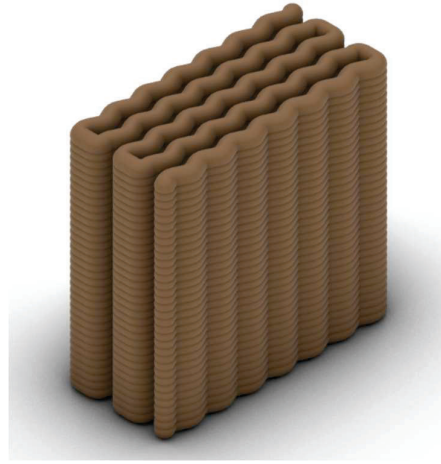
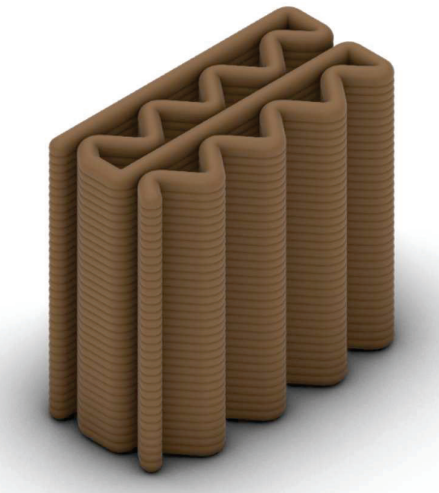
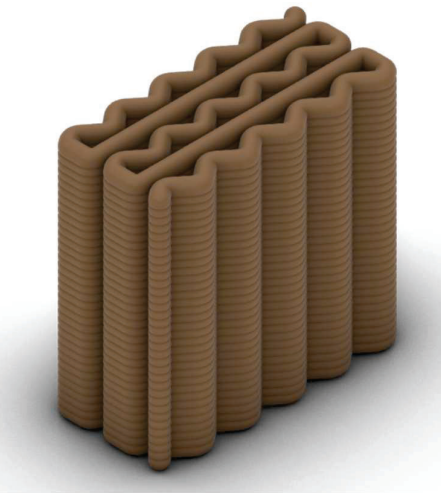
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A
ANNEXES

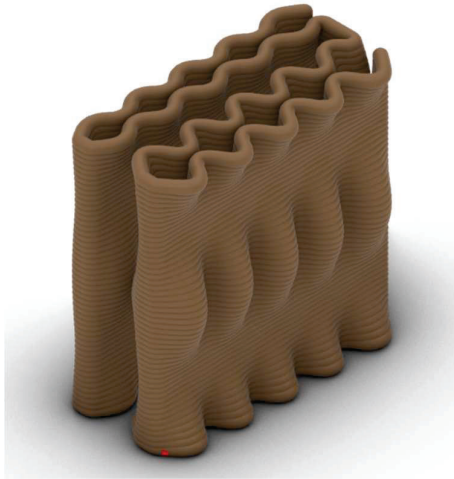
A.1. ISOMETRIC IMAGES OF 3DP GEOMETRIC ITERATIONS

Table 27 – Isometric images showing 3DP texture and side connections at wall terminations.

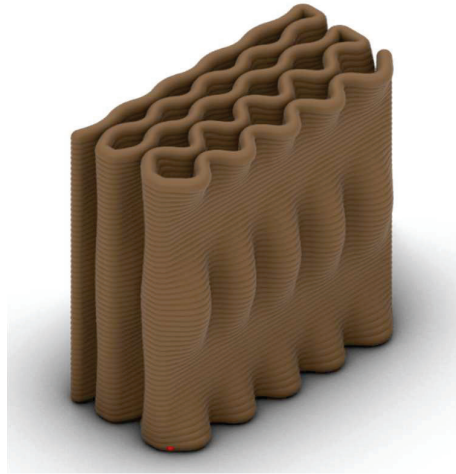
7A-3	7A-4
	
7A-5	7B-3
	

7B-4**7B-5****7C-3****7C-3A****7C-4****7C-5**

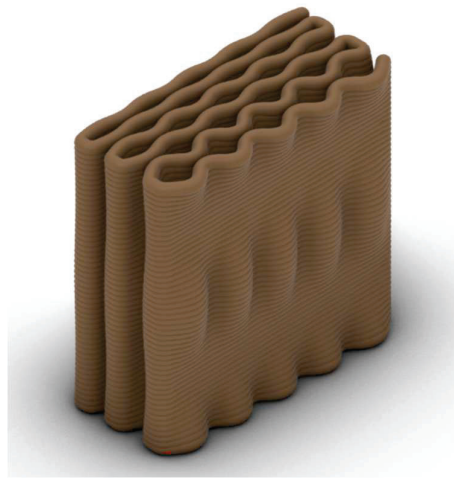
5A-4



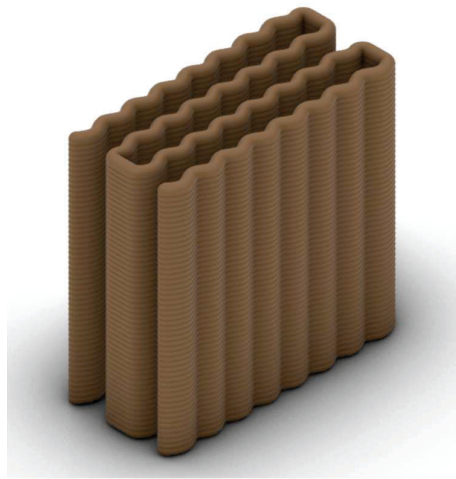
5A-5



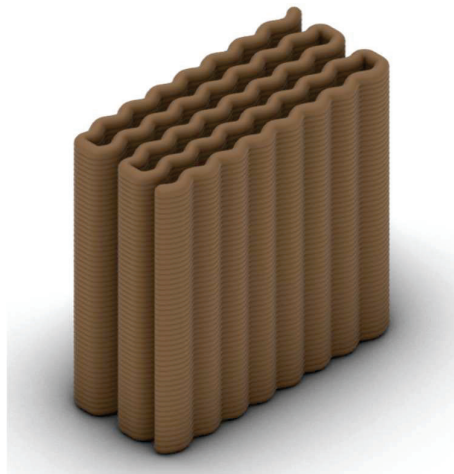
5A-6



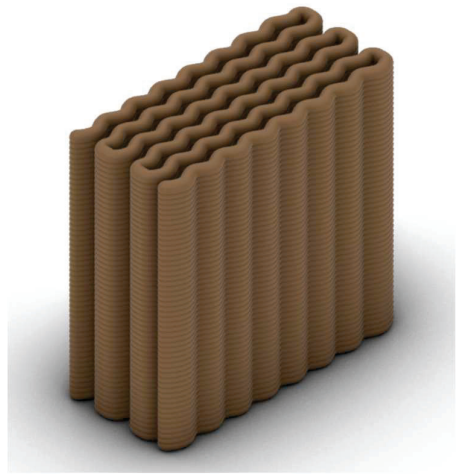
5B-4

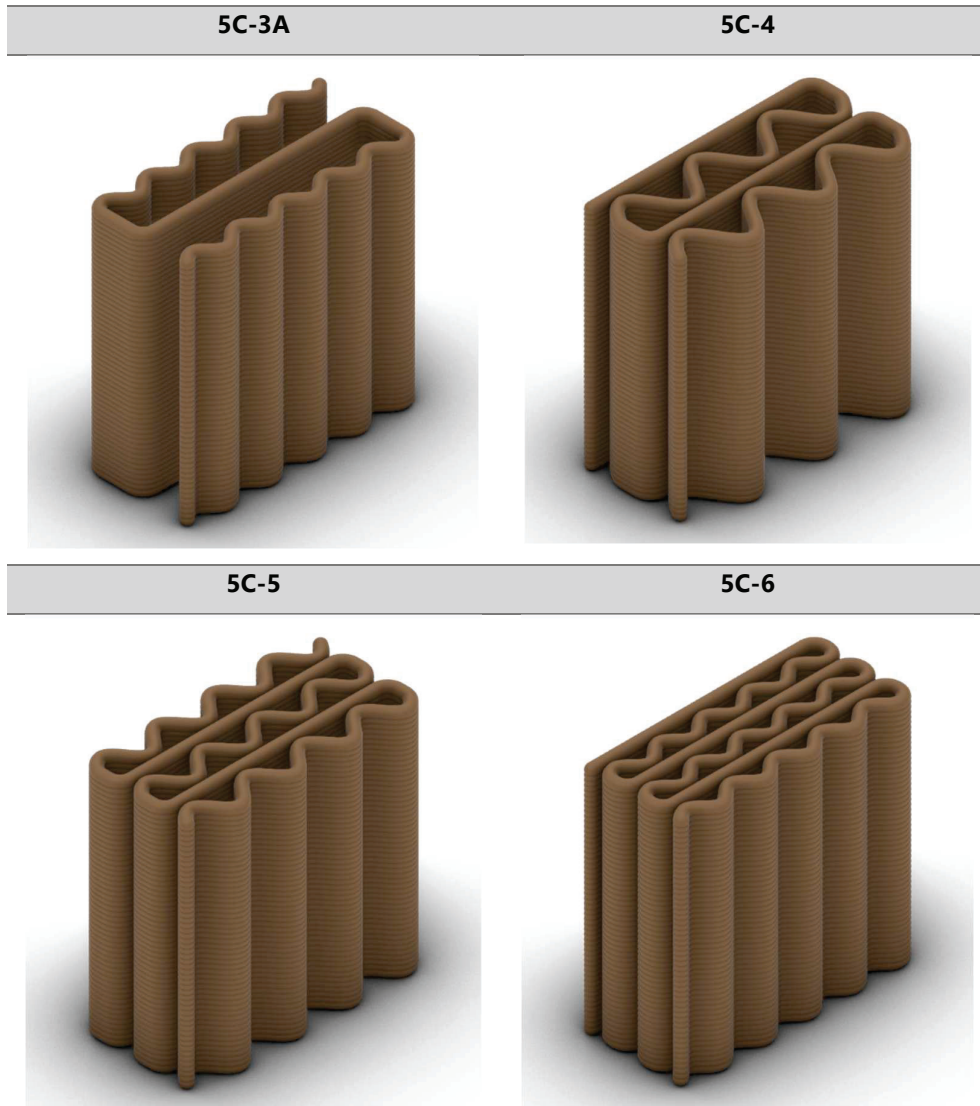


5B-5



5B-6





**Layer heights: 3cm for 7cm geometries;
2cm for 5cm geometries*

A.2. PREVIOUSLY CONSIDERED OPTIMIZATION OPTIONS

One of the biggest hurdles of the optimization is the manual nature of TRmesh, which requires baking of geometries, and its high sensitivity to meshing errors. These factors prevented automation, and the incorporation of simulation results as the fitness criterion for the mentioned optimization plugins.

Four options were previously considered:

1. Wallacei multi-objective optimization across all geometries and parameter sets - proved infeasible due to manual baking and meshing errors (Figure 75).
2. Wallacei parameter optimization within each geometry - also infeasible for the same reasons.

3. Galapagos single-objective optimization per geometry using thermal performance as the fitness function – not feasible as the same weaknesses of TRmesh prevent the fitness goal to be incorporated in the Galapagos optimization loop.
4. Manual iteration (the chosen final workflow) – parameters were manually adjusted in Grasshopper, followed by simulation in TRmesh/TRfem, and results were then compared across iterations.

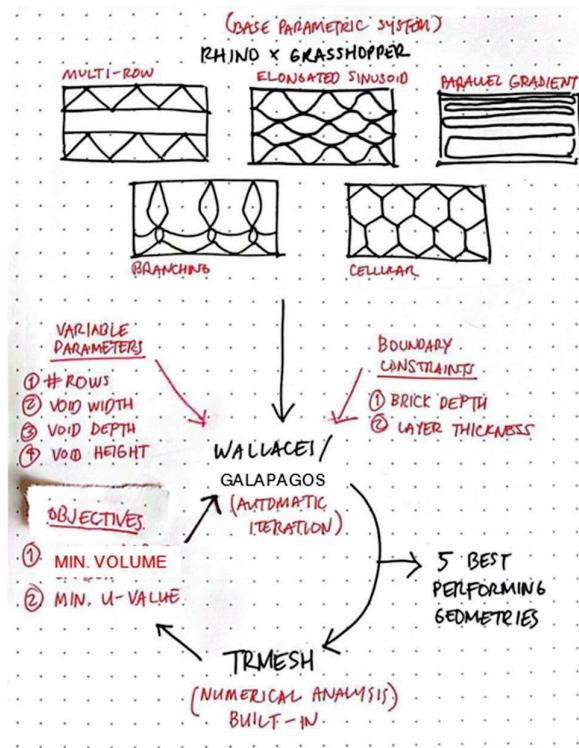


Figure 75 – Initial optimization loop using Wallacei/Galapagos. Was deemed infeasible due to limitations in the thermal performance plugin used. (Author's own).

A.3. AIR CONDUCTIVITY COMPUTATIONS

According to UNE-EN ISO 6946:2021 [15] Section 6.9, the values given in Section 6.9.2 and Table 28 below apply to an air layer which:

- is bounded by two faces that are effectively parallel and perpendicular to the direction of heat flow, and that have emissivities not less than 0.8;
- has a thickness (in the direction of heat flow) of less than 0.1 times each one of the other two dimensions, and not greater than 0.3 m; and
- has no air interchange with the internal environment.

If these conditions are not met, alternative procedures described in Annex D of the standard (below) must be followed.

According to Section 6.9.2 of the standard, an unventilated air layer is one in which there is no express provision for air flow through it. Values of thermal resistance are given in Table 28. The study takes

resistance values from the "horizontal" column, given the horizontal direction of heat flow considered for wall components.

Table 28 - Thermal resistance of unventilated air layers with high emissivity surfaces. [15].

Thickness of air layer mm	Thermal resistance m ² ·K/W		
	Direction of heat flow		
	Upwards	Horizontal	Downwards
0	0,00	0,00	0,00
5	0,11	0,11	0,11
7	0,13	0,13	0,13
10	0,15	0,15	0,15
15	0,16	0,17	0,17
25	0,16	0,18	0,19
50	0,16	0,18	0,21
100	0,16	0,18	0,22
300	0,16	0,18	0,23

NOTE Intermediate values are obtained by linear interpolation.

Annex D Thermal resistance of airspaces

For geometries where internal air voids do not meet the requirements of Section 6.9.2, Annex D was used to determine the thermal resistance of the airspace. According to the standard, an airspace can be either an air layer (which has a width and length both 10 times the thickness) or an air void (which has a width or length comparable to the thickness). The annex also stipulates that if the thickness of the air layer varies, its average value should be used to calculate the thermal resistance. Given the dimensions of the voids in the studied geometries, Section D.4 (below) was used as reference.

D.4 Small or divided unventilated airspaces (air voids)

For an air void that is not rectangular in shape, its thermal resistance can be taken as equal to that of a rectangular void which has the same area and aspect ratio as the actual void. The thermal resistance of the airspace, R_a , is then given by Equation (5):

$$R_a = \frac{1}{h_a + h_r} \quad (5)$$

Where R_a is the thermal resistance of the airspace, in (m²·K)/W, h_a is the conduction/convection coefficient, in W/(m²·K), and h_r is the radiative coefficient, in W/(m²·K).

h_a is determined by conduction in still air for narrow airspaces, and by convection in wide cavities. For calculations in accordance with the standard, it is the larger of $0,025/d$ and the value of h_a obtained from Table 29. In Table 29, d is the thickness of the airspace in the direction of heat flow, in meters, and ΔT is the temperature difference across the airspace, in kelvins.

Table 29 - Convective heat transfer coefficients for temperature differences larger than 5K. [15].

Direction of heat flow	h_a^a W/(m ² ·K)
Horizontal ($\alpha = 90^\circ$)	$0,73 \times (\Delta T)^{1/3}$
Upwards ($\alpha = 0^\circ$)	$1,14 \times (\Delta T)^{1/3}$
Downwards	$0,09 \times (\Delta T)^{0,187} d^{-0,44}$

^a Or, if larger than value from table, $0,025/d$.

h_r is determined by the formula below:

$$h_r = \frac{h_{r0}}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 2 + \frac{2}{\left(1 + \sqrt{1 + d^2 / b^2} - d / b\right)}} \quad (6)$$

$$h_{r0} = 4 \cdot \sigma \cdot T_{mn}^3 \quad (7)$$

Where h_{r0} is the radiative coefficient for a black-body surface, in $W/(m^2 \cdot K)$, σ is the Stefan-Boltzmann constant: $5.67 \times 10^{-8} W/(m^2 \cdot K^4)$, T_{mn} is the mean thermodynamic temperature of the surface and of its surroundings, in K, d is the thickness of the airspace, in m, b is the width of the airspace, in m, ε_1 , ε_2 are the hemispherical emissivities of the surfaces on the warm and cold faces of the airspace. ($\varepsilon = 0.9$ is usually appropriate for internal and external surfaces.)

Once the thermal resistance of the airspace is obtained, the thickness of the air void can be divided by R to obtain the thermal conductivity to be inputted in TRfem. This is based on the formula for thermal resistance [15]:

$$R = \frac{d}{\lambda} \quad (8)$$

This method provides a means to ensure that non-uniform air cavities are included in the thermal model and simulations, as they play a significant role in the overall performance of the wall. At the same time, it ensures that the resulting air conductivity captures the effects of conduction, convection, and radiation in the air voids, achieving a more realistic and holistic result.

A.4. GEOMETRY PREPARATION

Three initial modeling options were tested to determine the most appropriate meshing and simulation setup (Figure 76):

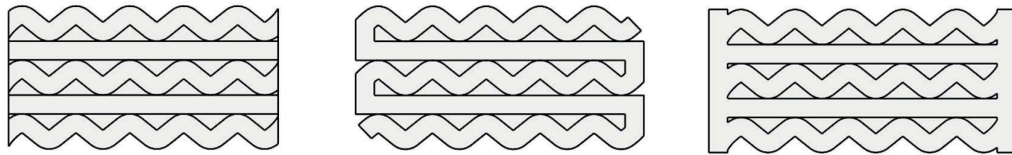


Figure 76 – Three initial modeling options: geometry without side connectors (left), geometry with side connectors (center), geometry with full side walls (right).

Because the side connections vary among the geometries, potentially affecting heat paths and results, it was decided that Option 1, without side connectors, would be used. This eliminates variability and complements the concept of on-site 3DP, where entire walls are printed as monolithic units. For this case, simulations focus on a central cut-out portion of the wall (measuring 1m long x 1m tall), avoiding the effects of edge terminations. However, in the case that future studies consider off-site printing in the form of blocks or bricks, side connectors or walls would then be necessary.

After finalizing the parametric design, the resulting volume or brep is baked into Rhino for further preparation prior to meshing:

- Use commands such as SimplifyCrv, FitCrv, or Rebuild to reduce the number of control points. This helps prevent meshing errors and decreases meshing time. These operations can also be performed within Grasshopper if preferred;
- Smooth or round any sharp edges or corners, as they may lead to mesh peeling issues during the meshing process. This step can also be executed in Grasshopper;
- Ensure that the brep is watertight, as TRmesh requires a closed polysurface to generate a valid mesh.

A.5. COMMON MESH GENERATION ERRORS

Common errors during mesh generation include:

- "Too many tets were peeled off" - typically occurs due to tight corners, too many control points, or insufficient mesh resolution. Can be resolved by "cleaning" the geometry, reducing complexity, or using a different mesh resolution (usually higher).
- "Part 0 is not a manifold mesh" and "Error computing the union of the input solids" - occurs when trying to mesh multiple solids. This limitation led to the development of a C# classification method for identifying air vs. solid tetrahedra after meshing (see Section 3.4.5.).
- "Not connected" or "self-intersections" - occurs when the geometry has self-intersections, preventing the mesh from being created. Can be resolved by "cleaning" the geometry or reparameterizing to prevent these instances. An example of this is shown in Figure 77.

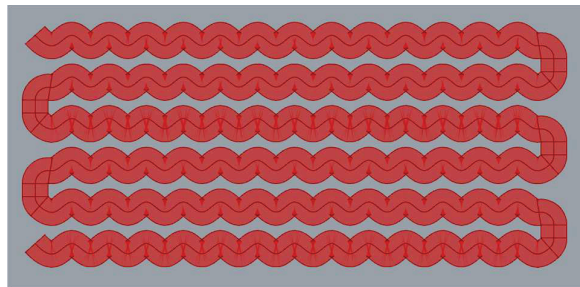


Figure 77 – Self-intersections present in the geometry need to be removed by reparameterizing.

- "Error: there is a triangle in the tet mesh that is used by more than two tetrahedra. We don't want that!" – meshing error. When this occurs it is recommended to remesh.
- "Resulting tet mesh was not very healthy" - indicates a suboptimal mesh. When this occurs it is recommended to remesh.

A.6. SIMULATION SETUP (TRFEM READER AND C# CODE)

In the Grasshopper TRfem script, the tetrahedral mesh from TRmesh and the air breps are used as inputs (shown in Figure 78). A custom C# script (Figure 79) was developed to classify each tetrahedron as either air or solid, based on the location of its centroid. If the centroid is found inside the air breps, the tetrahedron is classified as air and assigned the corresponding thermal conductivity for air. Otherwise, it is classified as solid and assigned the conductivity value for the earth material. An example classification is shown in Figure 80.

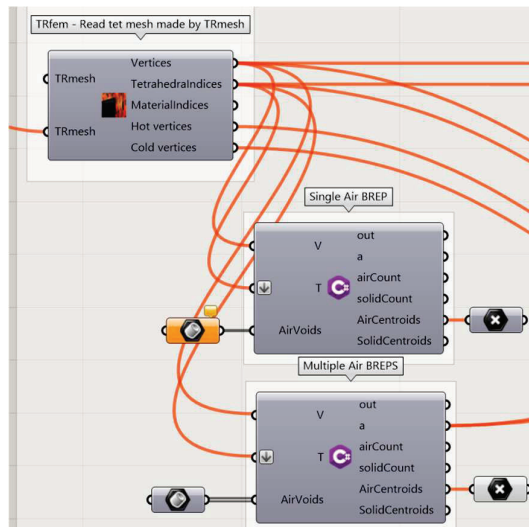


Figure 78 – Screenshot showing (1) TRfem mesh reader, where the mesh can be input, and (2) the C# component where Air BREPs can be input.

```

18 public class Script_Instance : GH_ScriptInstance
19 {
20     private void RunScript(
21         List<Point3d> V,
22         List<int> T,
23         List<Brep> AirVoids,
24         ref object a,
25         ref object airCount,
26         ref object solidCount,
27         ref object AirCentroids,
28         ref object SolidCentroids)
29     {
30         if (T.Count % 4 != 0)
31         {
32             a = "Invalid tetrahedra list: must be divisible by 4.";
33             return;
34         }
35
36         List<int> materialIndices = new List<int>();
37         List<Point3d> airPoints = new List<Point3d>();
38         List<Point3d> solidPoints = new List<Point3d>();
39
40         for (int i = 0; i < T.Count; i += 4)
41         {
42             // Get vertex indices
43             int i0 = T[i];
44             int i1 = T[i + 1];
45             int i2 = T[i + 2];
46             int i3 = T[i + 3];
47
48             // Get vertex positions
49             Point3d p0 = V[i0];
50             Point3d p1 = V[i1];
51             Point3d p2 = V[i2];
52             Point3d p3 = V[i3];
53
54             // Compute centroid
55             Point3d centroid = new Point3d(
56                 (p0.X + p1.X + p2.X + p3.X) / 4.0,
57                 (p0.Y + p1.Y + p2.Y + p3.Y) / 4.0,
58                 (p0.Z + p1.Z + p2.Z + p3.Z) / 4.0
59             );
60         }

```



```

61 // Collect points to test
62 Point3d[] testPoints = new Point3d[] { p0, p1, p2, p3, centroid };
63 int insideCount = 0;
64
65 foreach (Point3d pt in testPoints)
66 {
67     foreach (Brep airBrep in AirVoids)
68     {
69         if (airBrep.IsPointInside(pt, 1e-6, true))
70         {
71             insideCount++;
72             break; // No need to check other breps for this point
73         }
74     }
75 }
76
77 bool isAir = (insideCount >= 2);
78 materialIndices.Add(isAir ? 0 : 1);
79
80 if (isAir)
81     airPoints.Add(centroid);
82 else
83     solidPoints.Add(centroid);
84 }
85
86 // Output
87 a = materialIndices;
88 airCount = airPoints.Count;
89 solidCount = solidPoints.Count;
90 AirCentroids = airPoints;
91 SolidCentroids = solidPoints;
92 }
93
94

```

Figure 79 – Developed C# script for the classification of tetrahedra.

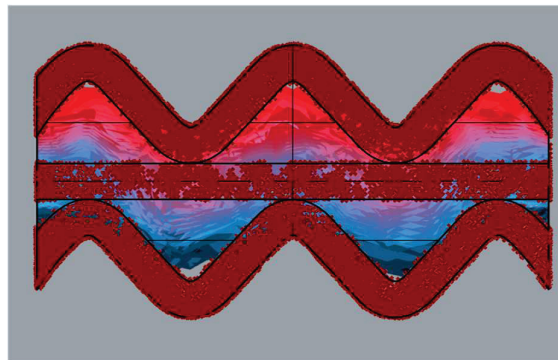


Figure 80 – Sample photo showing the centroids of the tetrahedra classified as “solid” (highlighted in red) based on the C# classification script. All remaining tetrahedra (not highlighted) are classified as “air”, and thermal conductivities are then assigned accordingly.

A.7. PARAMETERS FOR THE HOLISTIC EVALUATION

The parameters used for the holistic evaluation were obtained as follows:

- Print path length: This was obtained by adding the lengths of the contours of each geometry's surfaces, measured at their respective layer heights.
- Print volume: Calculated by multiplying the cross-sectional area of a single layer (for example, 7 cm x 3 cm or 5 cm x 2 cm) by the corresponding print path length.
- Printing time: Estimated using the Termite plugin in Grasshopper, which accounts for both the printing time and the travel time of the nozzle. A speed setting of 150 mm/s was used, based on a real-world 3D-printed housing product currently on the market (Havelar).

- Mass of earth: Derived by multiplying the print volume (in cubic meters) by the density of the earth mix, which was measured at 1789 kg per cubic meter.
- Mass of cork: Calculated by multiplying the volume of needed cork by its density (65 kg per cubic meter) [105]. This mass was then added to the earth mass in the three geometries that included insulation.
- Void percentage: Calculated by dividing the volume of the air voids by the total volume of the geometry (air voids plus print material).

This set of parameters forms the basis for a multi-dimensional evaluation of the wall systems, creating a more balanced assessment on performance, sustainability, and economy.