PARAMETRIC DESIGN FOR ADDITIVE MANUFACTURING: APPLICATION IN FACADE PANELS

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The increasing emphasis on sustainability and energy efficiency in the construction sector has driven the exploration of innovative solutions to enhance building performance. This study investigates the potential of additive manufacturing (AM) in constructing thermally efficient facade panels. Drawing inspiration from biomimetic principles, the research explores how hexagonal geometries, can optimise material usage and thermal performance while maintaining structural integrity; leveraging parametric modelling tools, such as Grasshopper, the study systematically iterates through geometric configurations to balance thermal resistance, material efficiency, and aesthetic objectives. The proposed panels incorporate surface reliefs and optimised internal voids to reduce heat transfer via conduction, convection, and radiation. A computational design framework integrates thermal simulations, solar radiation analysis, and structural considerations to validate design performance. Fabrication is executed using a robotic arm equipped with an extruder, enabling precise deposition of cementitious material and demonstrating scalable manufacturing processes without traditional formwork. Key findings highlight the interplay between geometry, material distribution, and robotic manufacturing, showing that advanced designs can achieve self-shading effects, reduce thermal bridging, and improve energy efficiency. Simulation results confirm the effectiveness of surface texturing and cavity optimisation in minimising solar heat gain and enhancing insulation properties. Despite printing tolerances and prototype scaling challenges, the study validates the feasibility of creating customisable, sustainable facade solutions for diverse climatic contexts. This research underscores the transformative potential of integrating biomimetic design, parametric optimisation, and additive manufacturing to redefine energy-efficient building envelopes. It sets the groundwork for future advancements in scalable, sustainable construction practices that address contemporary environmental and performance-driven challenges.

INTRODUCTION

The architectural and construction industry is undergoing transformative change driven by sustainability and efficiency. Optimising its thermal performance is essential for buildings accounting for significant global energy consumption. Among the most promising technologies addressing these challenges is 3D Concrete Printing (3DCP), which enables the creation of customised, energy-efficient building components with minimal material waste.

This study focuses on developing thermally efficient 3D-printed facade panels, leveraging biomimetic principles and parametric modelling to optimise their design and functionality. Inspired by natural structures, such as honeycombs, that exemplify minimal material use combined with excellent structural stability, this work explores how computational design and robotic fabrication can translate these principles into functional facade elements. By tailoring panel geometries to control heat flow and reduce thermal bridging, these innovations aim to enhance energy efficiency while maintaining structural integrity.

This research explores how computational design and robotic manufacturing can be combined to refine the production of facade panels. Parametric modelling tools like Grasshopper allow for the rapid iteration of panel geometries, optimising configurations to balance thermal resistance, material usage, and aesthetic requirements. Concurrently, robotic arms equipped with 3DCP extruders facilitate the precise deposition of cementitious materials, enabling the scalable fabrication of complex forms. This integration eliminates the need for traditional formwork, reducing construction timelines and costs.

Additionally, this research employs solar radiation simulations and thermal performance analyses to validate the proposed panel designs. The study simulates real-world conditions and assesses how hexagonal surface textures, optimised cavity configurations, and self-shading mechanisms contribute to enhanced insulation and energy performance [1]. These computational insights inform the design of prototypes, which are subsequently fabricated and evaluated for their thermal and structural properties.

This study presents a novel approach to developing thermally efficient facade systems customised to diverse climatic contexts by aligning parametric design, simulation-driven optimisation, and robotic manufacturing. This work contributes to the broader adoption of sustainable practices in the built environment, addressing the need for innovative solutions in new construction.

Considering these developments, the present research focuses on thermally efficient 3D-printed facade panels. Inspired partly by biological principles where organisms evolve structures that efficiently regulate temperature [2– 5], this work explores how biomimetic design strategies can be translated into facade elements.

El-Mahdy and Ali [1] developed 3D-printed clay facade components with a self-shading texture to reduce incident solar radiation, demonstrating how surface morphology can influence thermal performance. Brian Peters' "Building Bytes" [2] explored honeycomb-like ceramic brick modules fabricated via desktop 3D printers, leveraging the same geometry honeybees use to minimize material usage while preserving structural integrity. Briels et al. [3] investigated internal cellular patterns in lightweight concrete elements, illustrating that strategically placed voids can disrupt heat flow and enhance thermal insulation. This echoes the findings of Nazzi [4], who showed how honeybee hives achieve high load-bearing capacity and thermal stability through a purely natural hexagonal arrangement. Meanwhile, in the TerraPerforma project by IAAC [5], a complex 3D-printed clay wall with biomorphic surface features was tested in real-world conditions, showing that parametric design and robotic extrusion can integrate shading and ventilation strategies within a single facade system.

Taken together, these examples underscore the potential of biomimicry for guiding the shape and internal topology of 3D-printed facade elements. Much like honeybees or other organisms that evolve structures balancing thermal regulation and structural efficiency, these precedents highlight how carefully calibrated cavities, surface textures, and geometric configurations can reduce heat transfer, mitigate solar loads, and improve insulation. By embedding such natural principles into computational design processes, the present study seeks to refine 3D-printed facade panels that draw formal inspiration from biological systems and translate those natural efficiencies into tangible thermal benefits.

Through the synergy of computational modelling and robotic manufacturing, intricate surface reliefs and internal configurations can be generated to manage heat flow, reduce thermal bridging, and potentially limit building energy demands.

A critical aspect of this endeavour is finding design methods that minimise material use while maximising insulation performance. Parametric modelling facilitates the creation of minimal contact infills, where internal cavities and supporting trusses are strategically positioned to reduce conductive pathways. Additionally, surface texturing and patterning can influence convective and radiative heat transfer, offering the opportunity to tailor facade panels to different climatic contexts.

Beyond the design considerations, practical implementation depends on effectively using 3D concrete printing (3DCP) materials. This technology enables the precise extrusion of specialized mortars or concrete mixes layer by layer, paving the way for mass customization at the building scale. 3DCP can reduce material waste and enhance sustainability in the construction process by eliminating the need for one-off formwork or costly moulds.

The primary objective of this research is to design, and prototype a 3D-printed facade panel system that offers enhanced thermal performance compared to traditional solutions. In pursuit of this overarching goal, the study is divided into two subtasks:

Geometric and textural exploration

- Developing and testing geometries and surface reliefs that improve insulation properties, attenuate heat transfer, or enable beneficial air circulation on the facade's exterior.
- Employing biomimetic principles and parametric modelling to customise patterns for various environmental conditions.

Performance-driven optimization

- Optimizing the panel geometry to balance thermal insulation, structural adequacy, and minimal material usage.
- Validating the efficacy of proposed designs through simulation and, where feasible, initial physical testing. This involves analysing internal temperature gradients, energy usage, and material consumption rates.

Ultimately, the intention is to demonstrate that parametric design and robotic fabrication (through 3DP) can enable highly efficient, customisable facade panels suitable for new construction and retrofitting. By aligning architectural ambitions with engineering analysis, this research sets the stage for broader industry adoption, encouraging sustainable construction methods that leverage the full potential of emerging technologies.

LITERATURE REVIEW

The design concept for the facade panels emerged from a synergy of biomimetic principles, aesthetic influences, and technical insights gained from prior explorations of 3D-printed building components. While the natural honeycomb motif initially drew visual interest, it was ultimately chosen for its functional performance benefits. In nature, honeycomb structures exemplify a mathematically efficient way to optimise storage space while maintaining structural stability. By distributing loads uniformly across hexagonal walls, honeycombs help minimise the total amount of material used [4]. This dual emphasis on visual order and material efficiency aligns with biomimetic design, in which geometric forms found in nature are leveraged to achieve tangible performance advantages. Indeed, previous studies of 3D-printed panels with hexagonal patterns [2,3] further support this approach, indicating how form and function can be integrated within a single geometric strategy.

Many precedents exist, such as the one by Brian Peters [2], where crafted 3D-printed ceramic bricks with hexagonal surfaces exhibit unique formal expression and functional attributes (e.g., permeability or shading). When oriented horizontally, these hexagons create an irregular yet distinctive surface; oriented vertically, their open cores facilitate air circulation and partial transparency. Nevertheless, precedents like these highlight practical challenges, particularly in establishing a continuous printing path: the extrusion path often requires duplication of specific layers. At the same time, puzzle-like interlocks can complicate toolpath planning.

These observations guided the pursuit of thermally efficient 3D-printed infill designs, as evidenced in projects such as IAAC's Terraperforma [5]. Terraperforma integrated physical tests and digital simulations to assess performance regarding solar radiation, daylighting, and structural stability. This framework gave special attention to limiting heat transfer and reducing weight, objectives that dovetail with ongoing investigations into thermal performance metrics for 3D-printed components.

Recent research underscores a series of core metrics, including U-value, thermal resistance, thermal conductivity, and hygrothermal properties, collectively defining a system's energy efficiency. The U-value measures the overall heat transfer rate through a building element, with lower values indicating more substantial insulation [6]. Thermal resistance represents the inverse of conductivity and gauges the ability of a material or wall configuration to resist heat flow. Studies by Marais et al. (2021) [7] demonstrate how reducing cavity sizes and strategically arranging them can lower U-values, as multiple air gaps impede heat flow via conduction, radiation, and convection. Hassan et al. (2024) [8] also highlight material advancements, such as refined printing technologies for managing cavity geometries to diminish thermal bridging and enhance energy regulation in building elements.

In parallel, hygrothermal properties influence the overall insulating efficiency of 3D-printed cementitious mortars. For instance, Pessoa et al. (2023) [9] characterised the thermal conductivity, specific heat capacity, dry bulk density, and water vapour permeability of a specialised mortar mix, finding that moisture content plays a pivotal role in insulation performance. Elevated water absorption leads to higher thermal conductivity and reduced efficiency, an issue that can be mitigated through advanced formulations designed to minimise moisture uptake [8].

Meanwhile, thermal conductivity (λ) is a fundamental indicator of a material's capacity to conduct heat, with lower values generally associated with superior insulation [10]. Cuevas et al. (2023) [11] explored lightweight 3D-printed wall envelopes using expanded thermoplastic microspheres (ETM), achieving notable conductivity reductions from approximately 0.74 W/(m·K) in conventional mixes to 0.45 W/(m·K) in the ETM-enhanced variant. However, balancing mechanical stability and manufacturability often requires trade-offs. For instance, while specific designs or additives (e.g., polyurethane foam infill) can significantly lower U-values, they may complicate printability, compromise structural performance, and introduce materials with less favourable end-of-life or recyclability characteristics.

Beyond straightforward cavity strategies, there is an increasing interest in complex geometries and facade designs that merge aesthetic expression with functional advantages. Leschok et al. (2023) [12] outlined a spectrum of Design-For-Additive-Manufacturing (DFAM) methodologies that employ topology optimisation, infill design, and toolpath planning to create customised facade elements. Researchers have sometimes embedded water circulation channels within 3D-printed walls, enabling active temperature control [13]. Although watertightness and printing precision can become challenging, these prototypes demonstrate the potential for multi-functional, mono-material facades incorporating insulation and heat storage in a single system.

Finally, generative design approaches facilitate multi-objective optimisation, concurrently addressing thermal efficiency, structural stability, and material consumption [7,12]. Tools like Grasshopper or Dynamo can rapidly iterate through geometric configurations by adjusting internal cavities or layer thickness to pinpoint designs that minimise heat transfer while maintaining adequate load-bearing capacity. Studies by Marais et al. (2021) [7] and Cuevas et al. (2023) [11] illustrate how systematically evaluating multiple parameters can yield various viable solutions for 3D-printed construction, each reflecting different trade-offs among insulation, durability, and feasibility [7,11].

In summary, the convergence of biomimetic geometries (e.g., hexagonal reliefs), innovative materials (foam concretes), and generative design points toward a robust framework for optimizing thermal performance in 3D-printed panels. Nevertheless, the literature highlights persistent challenges, including the need for large-scale validation, moisture control, and a balanced approach to mechanical properties. Building upon these precedents, the present work aims to refine puzzle-like interlocks, hexagonal surfaces, and parametric modelling techniques to achieve a thermally efficient, fabrication-ready facade panel prototype.

CONCEPT AND DESIGN

In the pursuit of creating a thermally efficient facade panel, two fundamental strategies were adopted:

- Surface Relief on the Panel: The first approach involves introducing relief features on the panel's surface to increase shading zones on the facade, thereby reducing direct exposure to solar radiation. Interior thermal comfort and energy efficiency can be enhanced by manipulating how sunlight strikes the panel.
- Infill Optimized for Voids, Interlocks, and Reduced Thermal Bridging: The second strategy emphasises maximising voids in the infill structure. Minimising direct contact points (thermal bridges) between the panel's layers and creating interlocks makes limiting heat transfer from the exterior to the interior possible. This improves the system's overall thermal efficiency and strengthens its insulation properties, thus supporting better energy conservation.

Hexagonal Geometry Inspiration

Nature frequently employs hexagonal patterns to maximise voids while ensuring structural resistance. Adapting this concept, a half-hexagon relief was integrated into each panel's top profile so that adjacent panels interlock and collectively form a continuous hexagonal surface (see Figure 1). Beyond achieving a formal expression, this hexagonal relief aids in shading the facade, helping maintain stable indoor temperatures and potentially reducing heating or cooling demands.

Each panel was designed to connect seamlessly with its neighbour, forming a cohesive overall surface. At the edges of the building facade, rounded panels provide a softer transition to the rest of the structure.

Puzzle-Inspired Interlocks

While the infill geometry itself did not follow a single direct inspiration, several solutions were studied, such as the one proposed by IAAC in their Terraperforma project [5]. The infill was developed to minimise contact points and, at the same time, incorporate puzzle-like interlocks (Figure 2). These puzzle joints ensure structural stability and facilitate easy panel assembly.

Parametric Schema

The parametric schema was refined to enable flexible dimension adjustments for the panel, improving design versatility and printing efficiency. This adaptability was used to fine-tune the model's specifications throughout optimisation, ensuring a more effective final print. The parametric approach facilitates customisation for different projects and performance requirements (Figure 3).

Seven parameters drive the geometry generation, three of these govern the panel dimensions (height, length, width), two parameters control interlocking features properties (interlock size, interlock gap), and the remaining are related to the printing constraints (extruder diameter).

- Height, length, width: define basic panel dimensions.
- Extruder diameter, interlock size, and interlock gap must be adjusted if the panel's width changes significantly, ensuring correct offsets and layer spacing.

To achieve a fully parametric model in future work, proportional relationships between panel dimensions and these printing parameters could be established. For instance, while the panel width is unlikely to exceed 300 mm, modifying the length should automatically adjust the interlocking geometry and its tolerances, ensuring proper fit and structural integrity.

Using the baseline rectangle, we identified critical points (mainly via the "move" command in Grasshopper) that, when connected, generate the printing path for each layer. The "hexagon depth" parameter controls the relief depth on the surface (Figure 4), but the maximum printable inclination on a vertical plane must be considered to prevent printing failures on sloped surfaces.

The side modules completing the facade are parametrically connected to the central module, which features the relief. The two side modules automatically reflect changes to the central module's design.

Therefore, the approach is organised into three main stages:

- Geometry Definition
  Each panel begins as a subdivided rectangular outline. Key points along the edges are strategically placed or shifted to form a hexagonal relief on the central panel or interlocking corners on the side panels. These points are then woven into continuous curves, which provide the basis for the final 3D shapes (Figure 4).

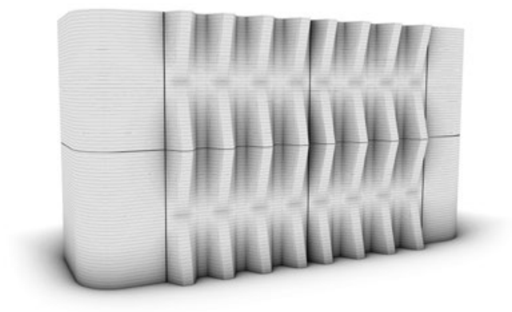


Figure 1: Representation of the connected facade panels.

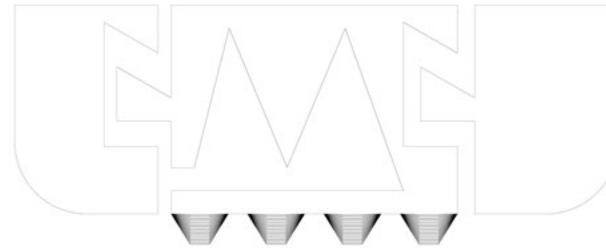
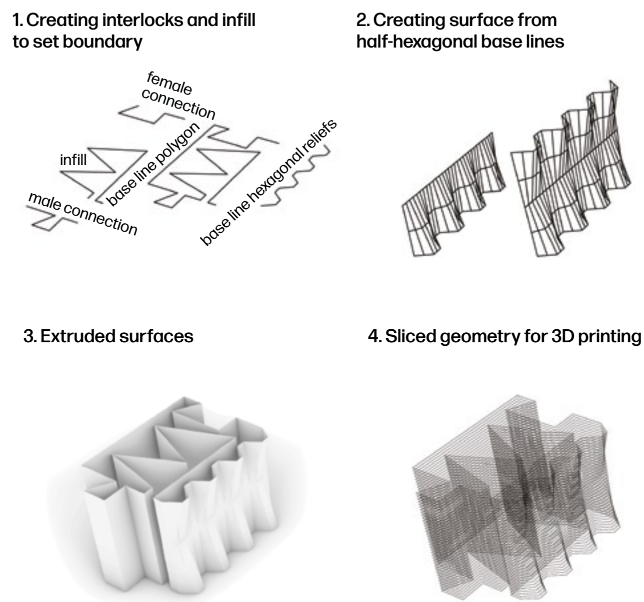


Figure 2: Plan view of the facade composition with two rounded side panels and one central relief panel.

Parameters inputs:

1. Panel height
2. Panel lenght
3. Panel width
4. Nozzle diameter
5. Hexagonal srf. depth
6. Fitting depth
7. Fitting tolerance



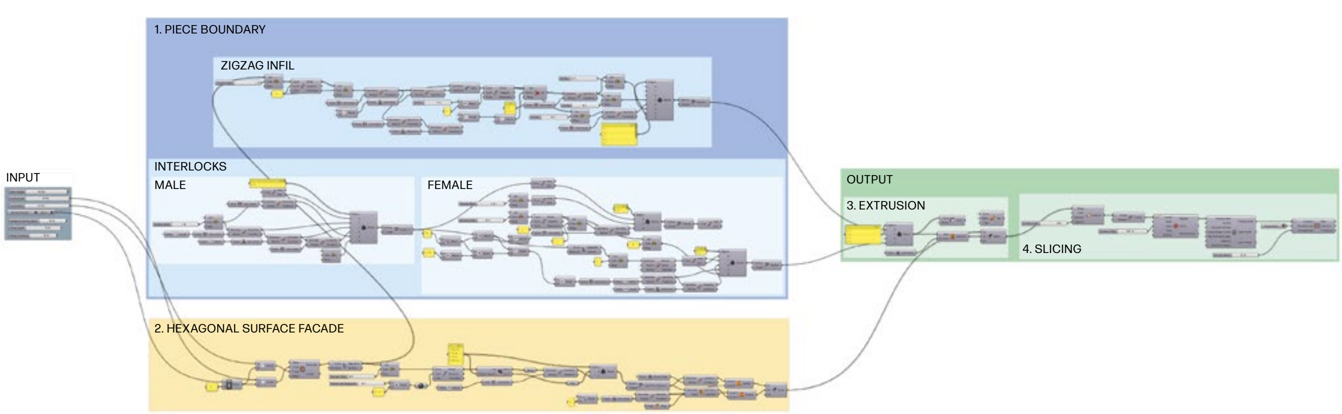


Figure 3: Parametric schema for panel generation, its printing path and overall view of the GH model.

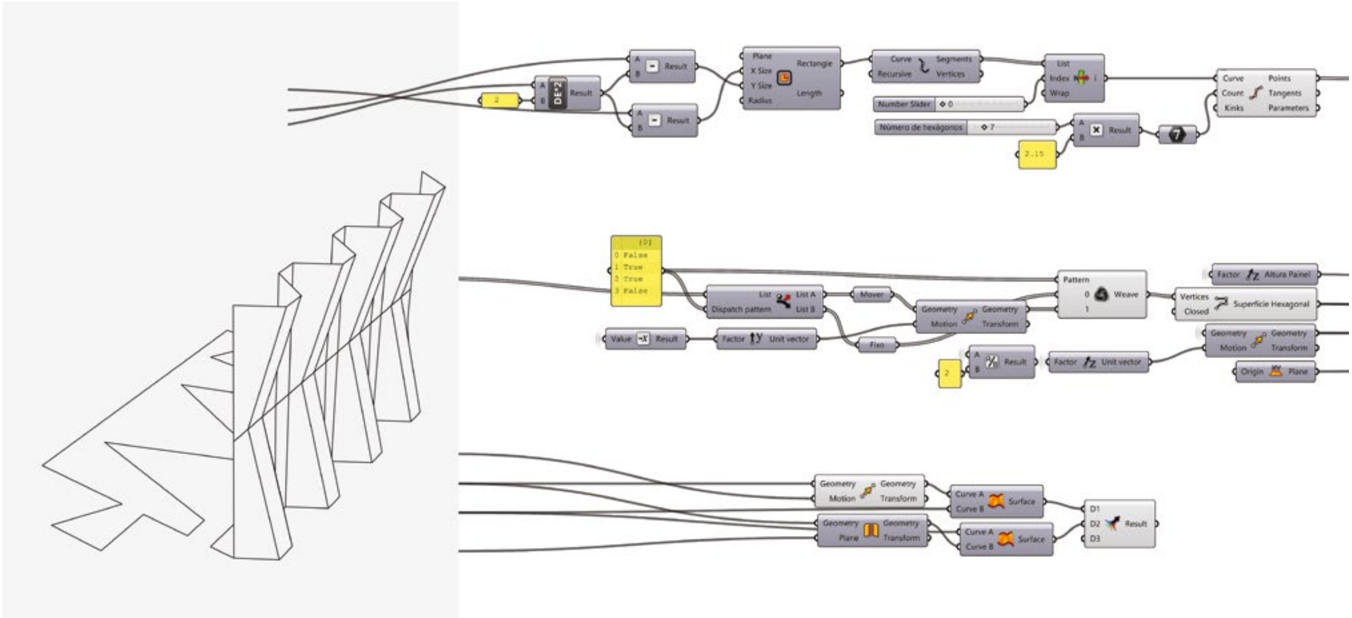


Figure 4: Model visualisation and computational model for generating the panel's relief surface.

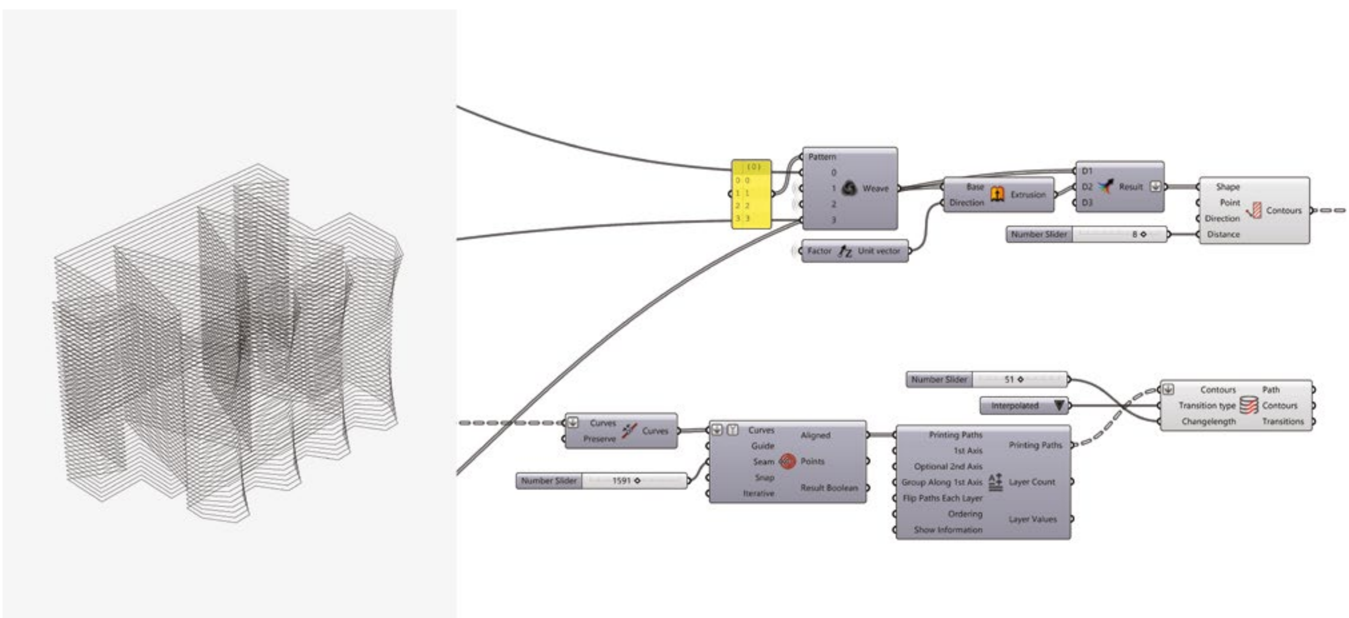


Figure 5: Model visualisation and central panel computational model of the printing path.

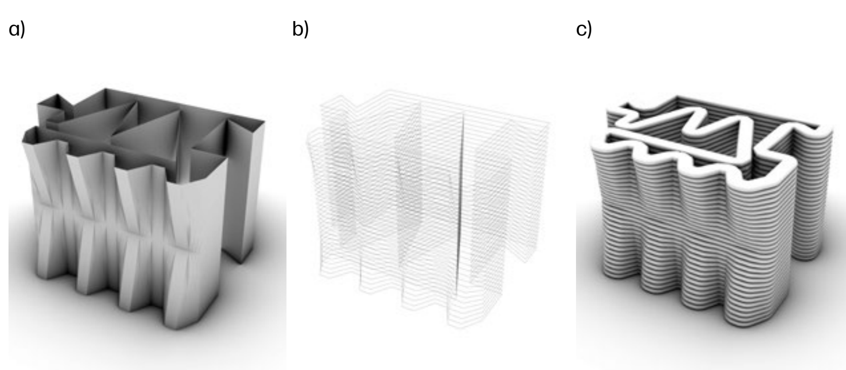


Figure 6: Digital prototypes of the central panel pieces: a) geometry, b) slicing with printing path and c) printed layers visualisation.

- Printing Path Planning
  Once the curves are generated, they are extruded to match the panel's intended thickness and height, accounting for a nozzle diameter of 15 mm (Figure 4). Spacing of approximately 30 mm reduces internal deformation and ensures consistent layer deposition. The resulting polylines define the extrusion paths in red in the Grasshopper previews to facilitate a straightforward, repeatable printing process (Figure 5).
- System Modularity
  A similar parametric logic governs the design of side panels, ensuring that relief patterns and edge profiles fit neatly with the central panel. Interlocking edges and inclined surfaces are incorporated into the same script, enabling each panel to align precisely without extensive manual adjustments.

PROTOTYPES PRODUCTION

In refining the parametric schema described above, modifications were made to inclination angles and hexagon positioning to optimise structural stability and increase solar protection. During the iterative design process, it became evident that adjusting these parameters was crucial for achieving a panel featuring prominent texture for self-shading, especially during the Spring and Summer season (April–September).

Shaded surfaces reduce direct solar exposure and alter how heat waves travel, enhancing heat absorption and dissipation and delaying penetration into interior spaces. Furthermore, when surfaces are more irregular or protruding, there is a larger surface area in contact with air, facilitating heat dissipation. These protrusions also promote convective air currents, where cooler air replaces rising warm air, lowering temperatures around the structure and improving interior thermal comfort.

These pieces were modelled in Rhinoceros 3D, and the KRL code was generated via Grasshopper (Figure 6 a)) through the curves in Figure 6 b). The 3D model of the final piece to be printed is shown in Figure 6 c).

Equipment, Materials, and Printing Parameters

A KUKA KR 120 robotic arm was coupled to an MAI MULTIMIX-3D mixer and pump. During pre-printing, the pump and hose connected to the extruder were lubricated using slurry to ensure smooth operation. For the actual printing process, the following parameters were used:

- Extruder nozzle diameter: 15 mm
- Layer width: Between 25 mm and 30 mm
- Layer height: 8 mm
- Water flow rate: 265 L/h
- Pump frequency: 15 Hz
- Robotic printing speed: 100 mm/s

Despite these adjustments, there were limitations during fabrication. When scaled down to a small prototype, the slope on the front face, meant to improve self-shading, didn't create the desired visual depth. The connections, designed as male-female interlocks between modules, also faced issues due to variations in layer width and print consistency, making the fit unreliable. As a result, the module looked blocky, and the intended thin, interlocking facade segments were not achieved.

Future designs could try L-shaped or other geometric connections to address these issues. Printing only a tiny part of the facade made it difficult to see how the modules would come together. A larger-scale print or building the complete facade would better show the self-shading effects and test how well alternative connections work. The three module types (left edge, central with relief, and right edge) are shown in Figure 7.

Lastly, the mortar showed good quality thanks to careful laboratory testing and precise water dosing during preparation. The 15 mm nozzle proved well-suited for the chosen geometry and the viscosity of the cementitious material, allowing for consistent layer deposition. Another advantage was the rapid production time, illustrating the efficiency of this fabrication method.

SIMULATION

Evaluating building components for thermal performance is critical for ensuring their efficacy in real-world applications. This study employed simulation methods to assess the thermal and solar radiation performance of the proposed 3D-printed facade panels. These simulations aim to validate the effectiveness of the geometric features, such as surface reliefs and infill configurations, in reducing heat transfer and optimising energy efficiency.

The research utilised computational tools and plugins integrated with Rhinoceros 3D and Grasshopper, specifically Ladybug, for solar radiation analysis and TRmesh for thermal evaluation. These tools were selected for their ability to model complex geometries and perform detailed environmental simulations, enabling iterative refinements to the panel designs. TRmesh is a tetrahedral meshing engine and plugin for Rhinoceros 8, developed to facilitate volumetric thermal modelling, a crucial aspect for assessing heat dissipation and energy performance in complex architectural geometries. This approach aligns with the principles outlined by Fuchs (2022) [18], which emphasises the necessity of volumetric thermal modelling over traditional methods that often rely on simplified 2D approximations, potentially sacrificing accuracy when dealing with intricate forms [18].

The simulations were conducted with two primary focuses:

- Solar Radiation Analysis: Assessing the self-shading potential and irradiance distribution on the panel surfaces to reduce solar heat gain and enhance interior comfort. This involved testing the facade design under various sun positions and climate conditions specific to Porto, Portugal.
- Thermal Performance Evaluation: Evaluating the ability of the panels to minimise thermal bridging and enhance insulation properties. This included exploring internal heat transfer through the panel's geometry and infill design.

While the solar analysis yielded valuable insights, the thermal simulation results were inconclusive due to technical challenges associated with the complexity of the 3D models. The issues primarily arose from mesh generation and geometric compatibility with the simulation software, highlighting the need for improved workflows and software adaptations.

The following sections detail these simulations' methodologies, tools, and findings, along with the limitations encountered and potential pathways for future refinement.

Solar Analysis

A digital solar radiation assessment was performed on the panel surfaces to evaluate self-shading potential and reduce solar exposure, thus enhancing interior thermal comfort. The Ladybug plug-in for Grasshopper was used to simulate microclimatic data at varying levels, following the methods of Fleckenstein et al. [14] and Maksoud et al. [15]. Although this study did not focus on external site factors or building context, these methods can be scaled up to real-world conditions.

A generic, modular deployment was chosen as the case study, illustrated in Figure 8 and Figure 9.

Historical climate data for Porto, Portugal, spanning 1980 to 2016 (Figure 10), was analysed to identify the warmest period of the year. Based on this data, the period between April 1 and September 30 was selected for the simulation. The simulation was conducted using Ladybug, a Grasshopper plug-in that imports EnergyPlus Weather Files (EPW) and allows users to perform a range of environmental simulations and analyses. Specifically, Ladybug's tools enabled the selection of the analysis period and visualisation of weather data, making it ideal for supporting decisions during early design stages.

In this study, the EPW weather file for Porto was transformed into a WEA object using Ladybug's tools, allowing for the selection of a specific time range corresponding to the warmest months. While the simulation focused on average temperatures (18°C to 24°C), the analysis did not include factors like wind, pressure, and humidity, which also influence thermal comfort.

The building was oriented along a North-South axis, and a parametric schema for solar analysis was set up to perform the solar analysis. This method requires several input parameters, including weather files and analysis periods.

Direct sun hours (Figure 12) were also examined to assess daylight exposure and its impact on thermal comfort and solar energy potential. The heat-map visualisation, along with the Grasshopper script, shows that over the tested period some areas (specially on the roof) receive considerably more sunlight. For Porto, the simulation showed a peak of 343 hours of direct sunlight during the analysis period, highlighting opportunities for natural lighting and solar energy use, while also emphasizing the need for effective shading to prevent overheating. Comparing these results with historical averages is important for adapting the design to the local climate.

Ladybug's solar radiation simulation was used to show how the facade's textured surfaces receive and distribute solar energy over time. The solar radiation simulation on the textured facade revealed that applying surface relief can significantly reduce direct exposure in critical areas. The simulation results, although combining total solar radiation without differentiating between direct and diffuse components, provide a clear overview of how the textured facade modulates irradiance across the envelope.

Specifically, when texture is applied to the facade, incident solar radiation ranges from 0 kWh/m² in well-shaded areas to approximately 652.58 kWh/m² on the most exposed southern facade. In addition, cumulative direct sun hours may go to almost 300 hours over the analysis period.

These findings underscore the effectiveness of facade texturing as a solar management strategy, improving interior thermal comfort and offering valuable insights for optimizing solar energy usage in the design process.

Thermal Analysis

A thermal analysis of the walls was deemed crucial for evaluating the facade's performance. To this end, the TRmesh plug-in for Rhinoceros 3D was initially employed to estimate the thermal behavior of the irregular solid geometries using a fuzzy-mesh approach (Figure 13). The goal was to simulate the thermal exchange across the faade panels and identify design implications for improved performance.

During this process, some software limitations were encountered regarding mesh generation and the selection of internal versus external faces for TRfem analysis in Grasshopper. In response, alternative approaches were tested, such as simplifying the original geometry and adjusting TRmesh parameters (e.g., resolution) to better suit the analysis. As a workaround, the simplified panel geometry was then exported to Therm for thermal simulation. However, because Therm tends to favour 2D, orthogonal layouts, the resulting simulation yielded only a rough estimation of the thermal behaviour.

At this stage, the thermal analysis provides preliminary insights into how the textured facade may perform, which is an important aspect to be investigated more in-depth in the near future. These early findings highlight the need for further

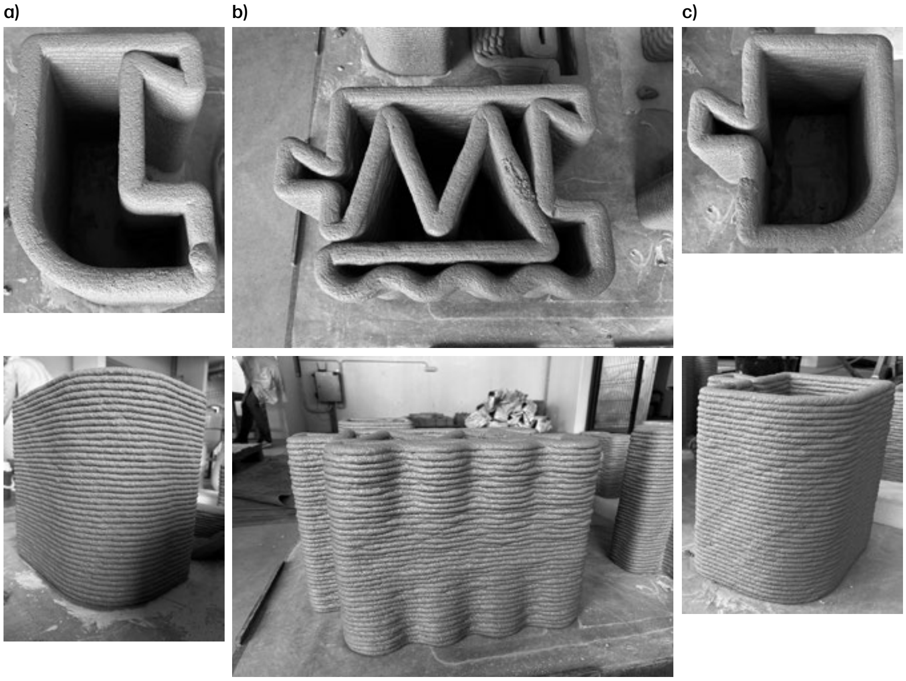


Figure 7: Panels printed with Weber 160-1 mortar: a) and c) corner panels; b) central panel.

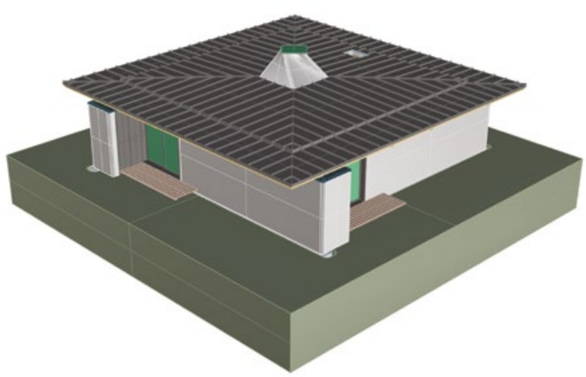


Figure 8: A base design for the case study. Font: Havelar [15].

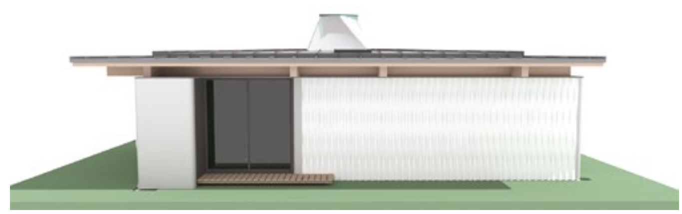


Figure 9: Final panel prototype applied to the case study.

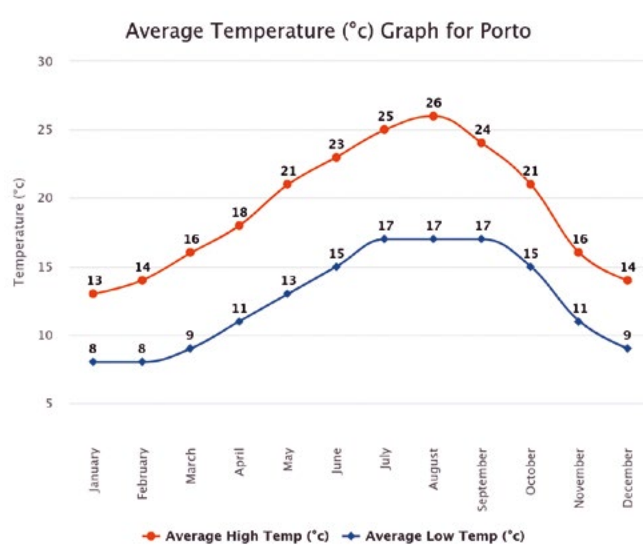
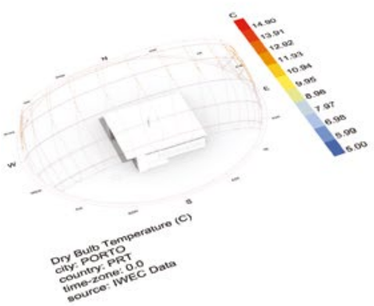
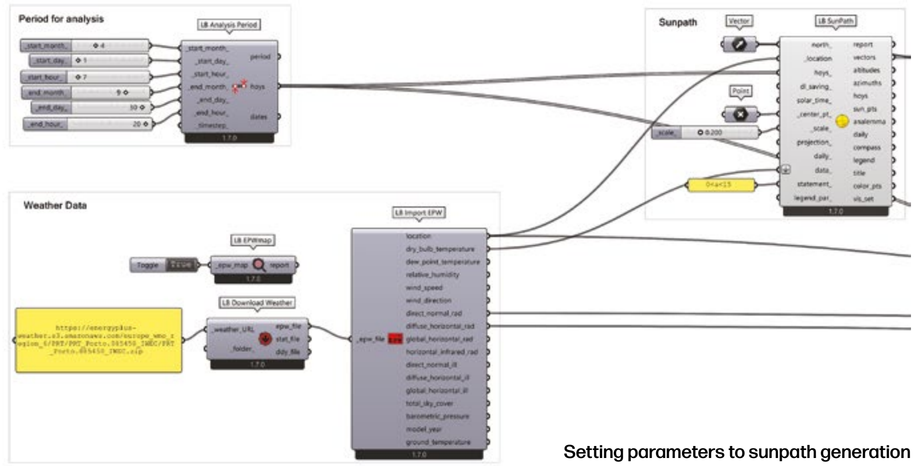


Figure 10: Average annual maximum (red) and minimum (blue) temperatures for Porto, Portugal [18].

Model visualisation



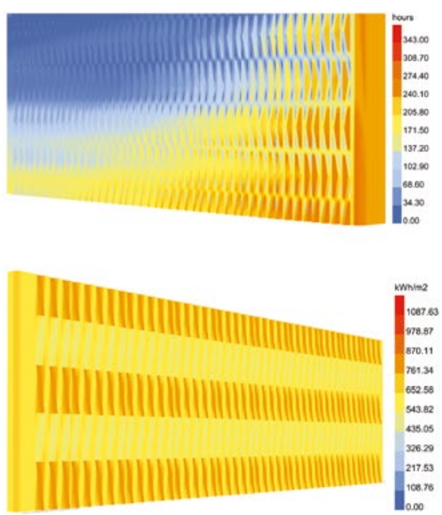
Grasshopper script



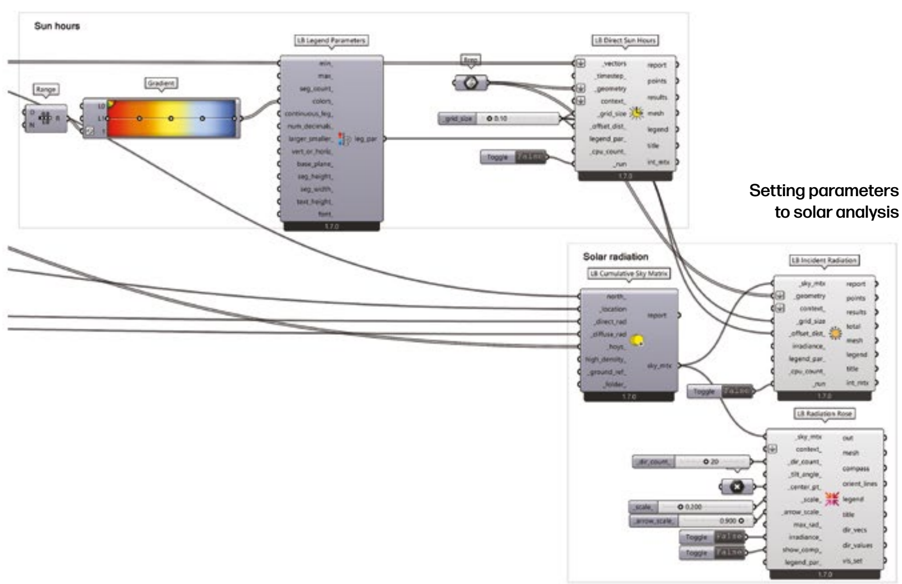
Setting parameters to sunpath generation

Figure 11: Graphical output and Grasshoper script of ladybug's simulation of the solar path between April 1 and September 30, from 07:00 to 20:00.

Model visualisation



Grasshopper script



Setting parameters to solar analysis

Setting parameters to radiation analysis

Figure 12: Graphical output and grasshopper script of direct sun hours analysis and radiation simulation.

a) b) c)

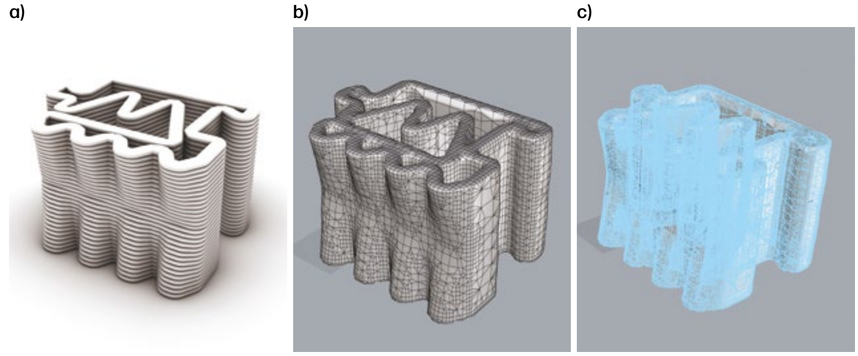


Figure 13: Initial thermal simulation of the wall using the TRmesh plug-in in Rhinoceros 3D: a) original solid geometry, b) simplified polygonal surface, c) mesh generation.

refinement of the computational workflow and the exploration of more robust simulation tools to fully capture the complex thermal interactions of the facade design.

Although a detailed thermal analysis proved challenging, this work underscores the attempt to explore innovative and sustainable solutions in construction. Further development of reliable meshing methods for complex geometries remains a key area for future research.

FINAL REMARKS

This study explored the potential of AM and parametric design to create thermally efficient facade panels. Drawing on biomimetic principles and leveraging computational tools, the development and fabrication of prototype panels featuring hexagonal surface reliefs and optimised infill geometries was proposed. While these approaches showcased promising opportunities for customisation and sustainability, several challenges and areas for improvement were identified.

Thermal simulations were conducted to evaluate the performance of the proposed designs, and the results provided a preliminary estimation of thermal behaviour. However, due to the complex geometry of the panels, the current 3D modelling and meshing workflow (using the TRmesh plug-in) produced only a rough approximation of the thermal performance. These limitations highlight the need for further refinement of the computational pipeline to enable a more detailed and accurate thermal analysis, which will be an important focus for future research.

Despite these challenges, important insights were gained regarding the panel's design and fabrication. While structurally robust, the current zigzag-shaped infill pattern has numerous material contact points, facilitating thermal bridging and potentially undermining insulation performance. To address this, future iterations should explore alternative infill geometries with minimal contact areas or incorporate insulating materials, such as cork granulates, within the voids to enhance thermal resistance. Additionally, improving the design of the male-female interlocks is essential to ensure proper fit and structural cohesion during assembly.

The study also highlighted limitations in the self-shading effect of the hexagonal surface reliefs, particularly at small scales. Larger-scale prototypes or full-scale facade systems should be fabricated and tested to assess their shading and thermal performance under realistic environmental conditions.

Future work suggestions include:

- Resolve simulation challenges:
  Improve 3D modelling and meshing workflows to enable detailed thermal analysis.
  Validate the impact of reliefs and infill geometry on heat transfer through computational and experimental methods.
- Optimise infill design:
  Test alternative infill patterns with fewer thermal bridges.
- Enhance fabrication precision:
  Refine robotic extrusion paths to improve interlock tolerances and panel fit.
  Explore new nozzle designs or printing parameters to enhance dimensional accuracy.
- Scale-up testing:
  Develop larger-scale prototypes or complete facade assemblies to assess thermal and structural performance *in situ*.
  Conduct environmental simulations with real-world climatic data to validate proposed self-shading and insulation strategies.
- Explore advanced materials:
  Investigate cement-based mortars with improved thermal performance, such as lightweight aggregates or microsphere additives.

In conclusion, while this research demonstrates the potential of AM and parametric design in creating energy-efficient building envelopes, it also underscores the importance of iterative refinement and validation. Future efforts can build on this foundation by addressing the identified challenges and exploring new design strategies to develop scalable, sustainable, high-performance facade systems for diverse architectural contexts.

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REFERENCES

[1] D. EL-Mahdy, M. Ali, Assessing the solar radiation performance of self-shaded 3D-printed clay-based façades, Architectural Engineering and Design Management 20 (2024) 249–268. https://doi.org/10.1080/17452007.2023.2285325.

[2] Brian Peters, Building Bytes 3D printed bricks by Brian Peters, Building Bytes 3D Printed Bricks by Brian Peters (2012). https://www.dezeen.com/2012/10/31/building-bytes-3d-printed-bricks-brian-peters/ (accessed March 21, 2024).

[3] D. Briels, S. Kollmannsberger, F. Leithner, C. Matthäus, A.S. Nouman, O. Oztoprak, E. Rank, Thermal Optimization of Additively Manufactured Lightweight Concrete Wall Elements with Internal Cellular Structure through Simulations and Measurements, Buildings 12 (2022) 1023. https://doi.org/10.3390/buildings12071023.

[4] F. Nazzi, The hexagonal shape of the honeycomb cells depends on the construction behavior of bees, Sci Rep 6 (2016) 28341. https://doi.org/10.1038/srep28341.

[5] IAAC, TerraPerforma, 3D Printed Performative Wall (2016). https://iaac.net/project/terraperforma/.

[6] NBS. What is a u-value? heat loss, thermal mass, and online calculators explained, 2023.

[7] H. Marais, H. Christen, S. Cho, W. De Villiers, and G. Van Zijl. Computational assessment of thermal performance of 3d printed concrete wall structures with cavities. Journal of Building Engineering, 41:102431, 2021.

[8] Hassan, E. Rodriguez-Ubinas, A. Al Tamimi, E. Trepci, A. Mansouri, and K. Almehairbi. 3d printing in construction. Automation in Construction, 163:105417, 2024.

[9] S. Pessoa, M. Jesus, A. S. Guimarães, S. S. Lucas, and N. Simões. Experimental characterisation of hygrothermal properties of a 3D printed cementitious mortar. Case Studies in Construction Materials, 19:e02355, 2023.

[10] ScienceDirect. Thermal conductivity, 2023.

[11] Cuevas, J. Strzałkowski, J.-S. Kim, C. Ehm, T. Glotz, M. Chougan, S. H. Ghaffar, D. Stephan, and P. Sikora. Towards development of sustainable lightweight 3d printed wall building envelopes –experimental and numerical studies. Case Studies in Construction Materials, 18:e01945, 2023.

[12] M. Leschok, I. Cheibas, V. Piccioni, B. Seshadri, A. Schlüter, F. Gramazio, M. Kohler, and B. Dillenburger. 3d printing facades: Design, fabrication, and assessment methods. Automation in Construction, 152:104918, 2023.281

[13] M. V. Sarakinioti, M. Turrin, T. Konstantinou, M. Tenpierik, and U. Knaack. Developing an integrated 3D-printed façade with complex geometries for active temperature control. Materials Today Communications, 15:275–279, 2018.

[14] J. Fleckenstein, P.L. Molter, A. Chokhachian, K. Dörfler, Climate-Resilient Robotic Facades: Architectural Strategies to Improve Thermal Comfort in Outdoor Urban Environments using Robotic Assembly, Front Built Environ 8 (2022). https://doi.org/10.3389/fbuil.2022.856871.

[15] A. Maksoud, E. Mushtaha, Z. Al-Sadoon, H. Sahall, A. Toutou, Design of Islamic Parametric Elevation for Interior, Enclosed Corridors to Optimize Daylighting and Solar Radiation Exposure in a Desert Climate: A Case Study of the University of Sharjah, UAE, Buildings 12 (2022) 161. https://doi.org/10.3390/buildings12020161.

[16] Havelar. (n.d.). Havelar. https://www.havelar.com/

[17] World Weather Online. (n.d.). Porto Annual Weather Averages. World Weather Online.Retrieved April 9, 2025, from https://www.worldweatheronline.com/porto-weather-averages/porto/pt.aspx

[18] Fuchs, M. (2022). Conductive heat transfer in thermal bridges. Encyclopedia, 2(2), 1067–1081. https://doi.org/10.3390/encyclopedia2020067