A METHOD FOR DESIGNING A BREATHING MODULAR WALL

CELSO URROZ[1] and SHERMEEN YOUSIF[2]
[1,2]*Florida Atlantic University.*
[1]*urrozc2023@fau.edu, 0009-0005-5434-855X*
[2]*syousif@fau.edu, 0000-0003-4214-1023*

Abstract. This paper presents a design framework that reinterprets vernacular architectural principles and passive strategies for achieving ecologically-driven design. It focuses on developing a design workflow for a modular breathing wall design inspired by the traditional Iranian windcatcher, harnessing passive cooling strategies and adopting low-tech logic in design. The primary objective is to formulate a computational design workflow that integrates passive design techniques simulated using a parametric system and coupled with advanced environmental simulations. Through iterative design processes, parametric variations, airflow analysis and solar radiation simulation, the method is aimed at designing a series of modular blocks adaptable to various architectural applications. The work couples traditional wisdom with computational logic, attempting to contribute to the UN Sustainable Development Goals by promoting innovation and sustainable urban ecosystems. The research signifies a step towards a resilient architectural future, where design processes are driven by environmental performance and sustainability.

Keywords. Design Workflow, Modular Design, Passive Cooling, Robotic Fabrication, Vernacular Architecture.

1. Introduction

Escalating climatic issues and growing environmental awareness are steering a transition from the industrial to an ecological era in the built environment (Chiujdea & Nicholas, 2020). This emphasises the necessity for structures designed with heightened consideration for sustainability principles. As the architecture discipline has become more attuned to ecological repercussions, there has been a fundamental re-thinking of design approaches. Energy use, for which buildings account for 20-40% in developed nations, is on the rise, primarily due to needs for heating, cooling and air-conditioning (HVAC) systems (Pérez-Lombard et al., 2008). Addressing current and future environmental challenges requires improving efficiency in heating and cooling systems (Cojocaru & Isopescu, 2021). Also, there has been a shift towards passive design inspired by vernacular architecture and low-tech solutions, countering active thermal system dominance (Belmonte et al., 2021). Within this context, our research focuses on creating an ecological breathing wall prototype through computational logic and

ACCELERATED DESIGN, Proceedings of the 29th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2024, Volume 3, 253-262. © 2024 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

geometry figuration to leverage thermal regulation as a passive design strategy. The research aims to address questions regarding (1) the development of a design workflow informed by low-tech design and passive strategies, and (2) the computational requirements for pre-processing the resulting design for fabrication.

The primary research objective is the formulation of an innovative design workflow inspired by the traditional Iranian "Windcatcher (Badgir) and Qanat" system, using computational methods to improve thermal comfort. Emphasising the development of a comprehensive design system over mere artefact prototyping, this work encourages a broader reevaluation of design processes driven by innovative and low-tech passive design strategies.

Our research methods involve literature review, computational design experiments, and environmental simulations to create and assess a sustainable architectural prototype, and test the developed workflow. The aim is to contribute to global sustainable development, aligning with UN Sustainable Development Goals: fostering innovation in industry and infrastructure (Goal 9) and cultivating sustainable urban ecosystems (Goal 11). This contributes to the discourse on sustainable design and its crucial role in shaping a resilient future.

2. Background

Since the 1990s, with the rise of digital fabrication and the use of algorithmic modelling and parametric analyses in the 2000s, research in performance-driven design has exponentially expanded (Caetano & Leitao, 2020). Parametric modelling, simulation tools, and optimization algorithms empower architects to refine designs iteratively based on performance feedback (Kolarevic & Malkawi, 2005). However, recent interest in re-evaluating low-tech design and emphasising passive strategies over energy-demanding active ones (Abdelmohsen et al., 2019) is gaining momentum in novel computational design frameworks, e.g. (Antonini, Boeri, & Giglio, 2020; Yuan, Zhang, & Han, 2013).

While research on adaptive design workflows is increasing, the exploration of affordable low-tech design solutions in performance-driven design is still experimental. Recent literature emphasises the pivotal role of geometry configuration and computational logic for enhanced thermal properties in guiding the architectural design process. As such, this work aims to integrate geometry figuration and its thermal advantages towards low-tech performance-driven design, contributing to the needed shift to decarbonization. Such synergy becomes important in establishing environmentally conscious design approaches.

3. Research Method

Our research methodology involves developing a comprehensive design system, beyond a mere artefact prototyping. This integrative approach couples exploration with practical experimentation, distilling principles from vernacular architecture and integrating them into modern computational design processes. Our hypothesis was based on a theoretical exploration of passive cooling strategies found in traditional architectural elements. Experimentation involved studying vernacular design principles, focusing on their environmental logic and historical application for thermal comfort without the need for active cooling systems. As such, developing the method framework involved the following protocol (Fig. 1):

Phase 1: Modelling and Design Generation: We translated insights from vernacular strategies into a computational model, employing algorithmic design for design iterations and evaluation, in order to form-find and achieve successful geometry figuration and examining different surface manipulations (for thermal moderation of a breathing wall).

Phase 2: Design Qualifying and Environmental Simulation: Critical for evaluating the environmental performance of our proposed design, this phase involved employing advanced simulation tools to assess thermal and airflow dynamics, refining designs to maximise efficiency. The goal is to ensure that the breathing wall module's prototype is successful under various assembly configurations.

Phase 3: Pre-Processing for Robotic Fabrication: In this phase, we aimed to bridge the digital-to-physical gap by preparing our digital designs to be materialised through robotic fabrication. This entailed detailed design for translating complex geometries into physical forms, ensuring structural integrity and constructability. We also developed custom toolpaths for CNC machines like robotic arms, enabling precise fabrication of intricate design elements.

Phase 4: Testing: This process was intended to test the workflow components and integration of the three above-mentioned protocols. Additional testing is ongoing, which involves the fabrication of the wall's modules. This would mark the shift from theory and simulation to materialised application.

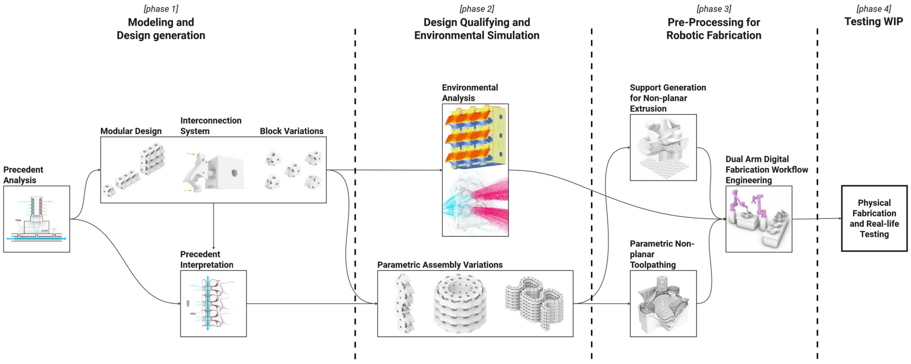

Figure 1: Diagram of the research method

4. Workflow Prototype

Our Workflow Prototype integrates traditional passive cooling strategies with modern design methodologies, focusing on the analysis of the Iranian windcatcher and its transformation into a scalable modular system.

4.1. ANALYSIS AND DESIGN INTERPRETATION

We analysed the natural ventilation principles of the Iranian windcatcher combined with a qanat to transpose them into a modular block for a panel system.

The windcatcher captures prevailing winds, scooping airflow through internal channels. When these winds interact with a nearby qanat—an underground water channel—due to convection, airflow causes cooling. Evaporation further enhances the cooling effect. The qanat not only contributes to thermal mass for temperature regulation but also facilitates drawing outside air into the building by creating an indoor negative pressure, achieving cooling. This energy-efficient system relies on natural processes without external energy input (Liu et al., 2024). We applied these principles to a modular wall design, introducing a 90-degree rotation of the windcatcher concept. In this adaptation, water flows vertically within the core, replacing the traditional horizontal underground flow. The central vertical water channel serves the function of the qanat. The block has two parts: the core and the cap, with the cap, a porous facade panel, acting as a windcatcher, guiding external air to engage with the water stream within the core. This design facilitates convection and evaporation processes inside the wall, offering a novel approach to passive cooling (Fig. 2).

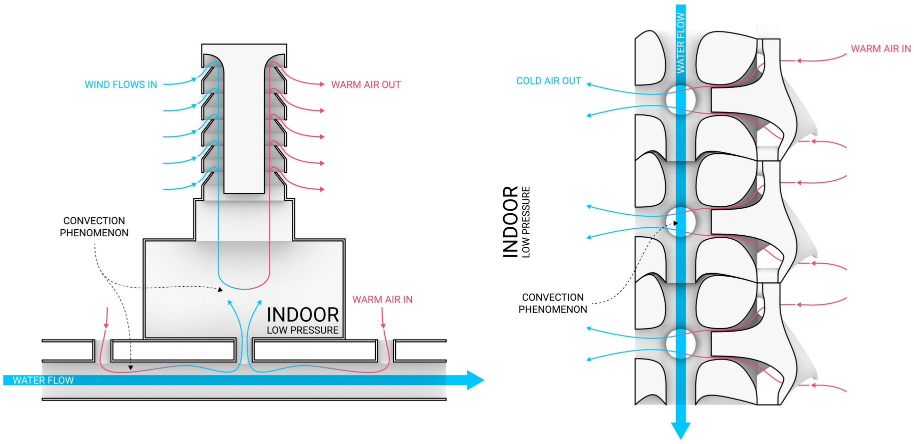

Figure 2: Diagram of the traditional Iranian windcatcher combined with a qanat on the left and our modern modular block system for enhanced passive cooling on the right.

Consequently, we created five modular block variations for diverse wall curvatures, airflow dynamics, and water circulation patterns, all derived from our 30x30 cm block curved by 30 degrees in four configurations (Fig. 3). We deliberately chose a 30-degree angle to limit deformation while enabling assembly curvature. This angle, being a dividend of 360 degrees, allows for symmetrical assembly configurations in the design process.

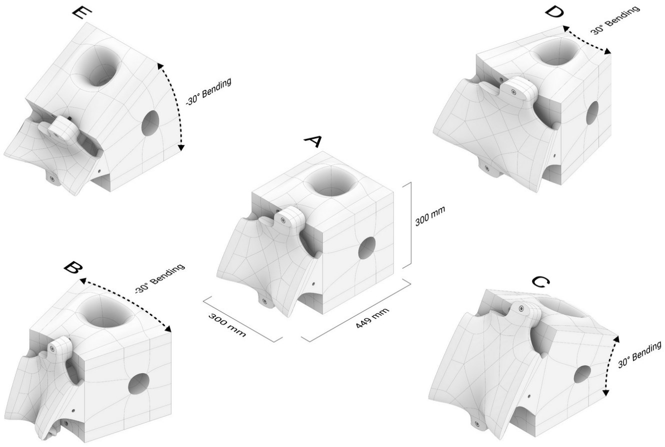

Figure 3: Collection of five modular block types, each serving a unique function.

The modular block interlocks with convex and concave shapes on the top and bottom, using a simple insert and bolt system (two 60mm M10 hex head socket screws for vertical connections and one 40mm M10 hex head socket screw for horizontal connections). A tab system among three consecutive vertical blocks enhances wall stability in a tilling fashion, enabling scalability from a single block to infinite configurations (Fig. 4). The selected overhang size minimises side airflow effects while maintaining adequate air intake, and a perforated core follows the same principle. Module cavities interconnect to form a pipe mesh for heat moderation and establish an air insulation layer.

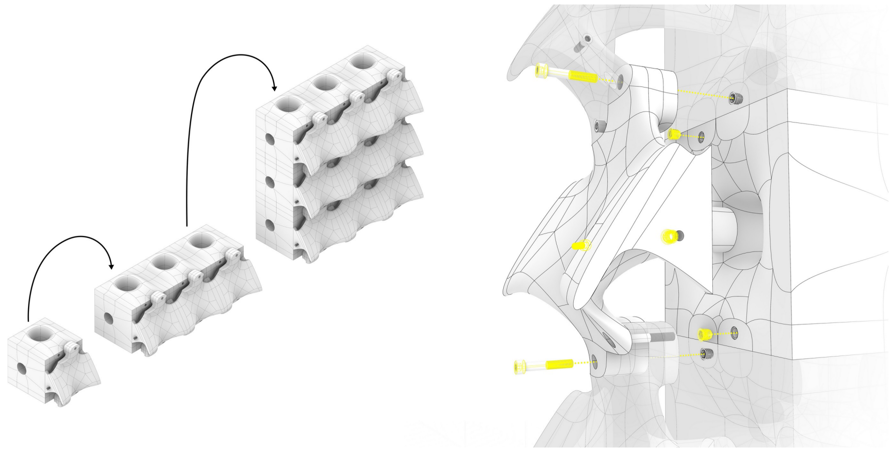

Figure 4: Left, assembly configurations; Right, close-up view of the straight block, showcasing the bolting system and interconnection interfaces.

4.2. ENVIRONMENTAL RESPONSIVENESS THROUGH DESIGN AND SIMULATION

This prototype development phase is aimed at qualifying the design against environmental performance metrics, particularly through parametric variations and solar radiation analysis and airflow studies. The process is focused on ensuring adaptability of the modular design, and its environmental performance.

In our modular block system, we created four wall configurations using five blocks, demonstrating their inherent versatility in configurations (Fig. 5). Modularity permits strategic alterations of block orientation and combination, offering flexibility to tailor designs to specific environmental conditions and spatial requirements. This feature optimises efficiency based on wall or panel shape, achieving diverse aesthetic and performance advantages.

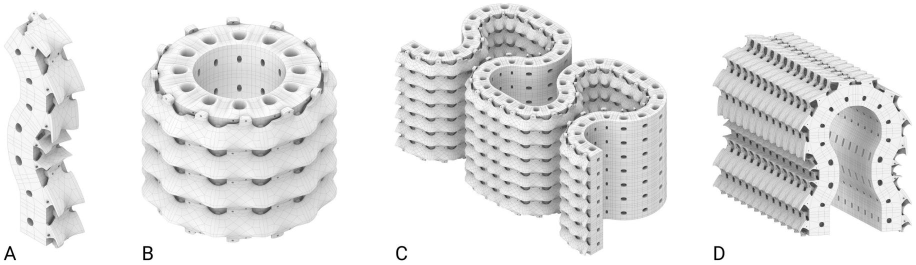

Figure 5: A., B. Assembly variation illustrating vertical curvature and horizontal curvature; C., D. Experimental assembly configurations for dynamic and sculptural shapes.

The solar radiation simulations revealed that the small-scale overhangs in the detail of the modular block, initially designed to protect the porous system from rain, also provide shading and enhance solar radiation dissipation. Acting as a natural shield, they reduce direct sun exposure, lessening the impact on the structure and improving insulation by minimising heat absorption of the wall. The overhangs' shading effect aligns with passive cooling principles, reducing heat absorption and creating a cooler micro-environment within the modular block wall by mitigating direct sunlight (Fig. 6). This positions the design as an environmentally responsive solution.

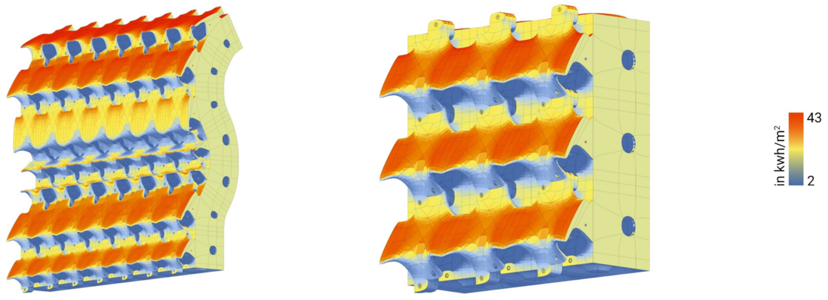

Figure 6: Solar radiation analysis, showing reduced solar heat gain in two configurations.

The airflow simulation reveals that the cavities feature a geometry channelling the air though the module's core to the indoor space. The cone-shaped tip of the panel, in conjunction with the water flow at the module's core, enhances air circulation through the venturi effect (Fig. 7).

This design significantly enhances energy efficiency compared with conventional HAVC systems. The deliberate shaping of cavities within the structure serves as a strategy to optimise airflow, ensuring a streamlined path through the module's core and into the indoor space. The cone-shaped tip of the panel, along with the water flow at the module's core, take advantage of the Venturi effect, where the constricted section accelerates air circulation by reducing fluid pressure, fostering a more effective exchange of heat and thereby improving the cooling process. By strategically utilising water flow to allow for a convection process, the design contributes to dissipating heat efficiently.

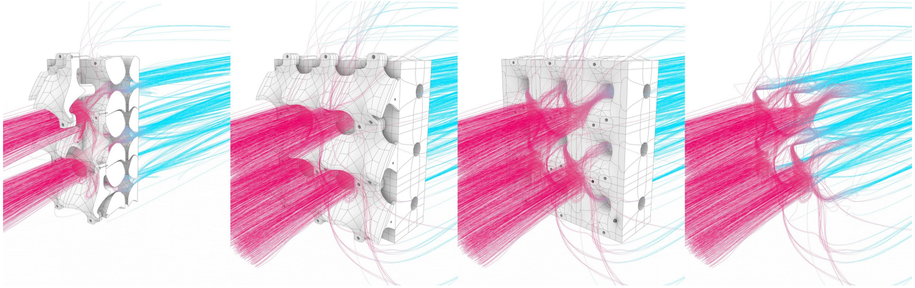

Figure 7: Airflow analysis of the modular block wall, simulating a temperature decrease.

4.3. PREPROCESSING AND SIMULATION OF ROBOTIC FABRICATION

To address the challenge of bridging between the design conceptualization and the tangible reality of fabrication, we broke down every element of the design into a set of machine commands tailored for the robotic fabrication processes.

Two pivotal technical aspects underpin our pre-processing efforts: to facilitate generation of a support design for non-planar extrusion and to achieve parametric non-planar toolpathing. Non-planar extrusion is essential for the creation of complex geometries that deviate from traditional layer-by-layer printing, allowing for the production of more nuanced and organic forms.

4.3.1. Support Design Generation for Non-Planar Extrusion

To ensure the integrity of the blocks during the complex extrusion process, we need a support structure. Designed, this parametrically Grasshopper-generated support structure can adapt to various surfaces (Fig. 8). The parametric generation process involves projecting an array of points onto a supported surface, followed by the creation of a patch using the resulting point topology. This support essentially becomes the surface on which the facade panel is printed. Before initiating the extrusion process, we use a standard 3D printer to fabricate this support. After securing it onto the workbench, we calibrate the robotic arm to precisely execute the printing of the facade panel with our bio-material substrate.

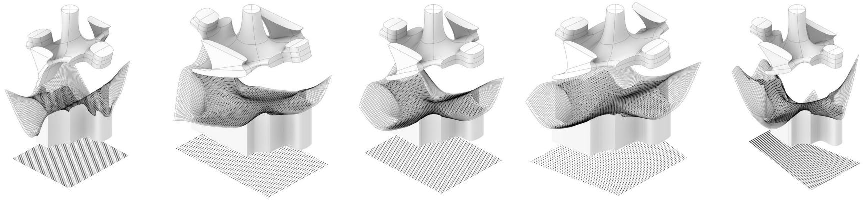

Figure 8: Design process of the support structure for the robotic extrusion of our 5 different facade panels.

4.3.2. Processing for Toolpathing

Next was the parametric non-planar toolpathing, where our custom Grasshopper script computationally generates toolpaths guiding robotic arms in three-dimensional space with precision. The parametric nature of these toolpaths allows rapid adjustments to design and material, fostering a flexible and responsive fabrication workflow. A layer height of 7 mm is employed. For the panel, we have opted for a solid base composed of 5 horizontal contour layers spaced 5mm apart. This configuration is chosen to maintain structural integrity (Fig. 8). From the 6th layer onward, we decided to employ only vertical concentric contouring. This choice is made to preserve weight and enhance fabrication speed.

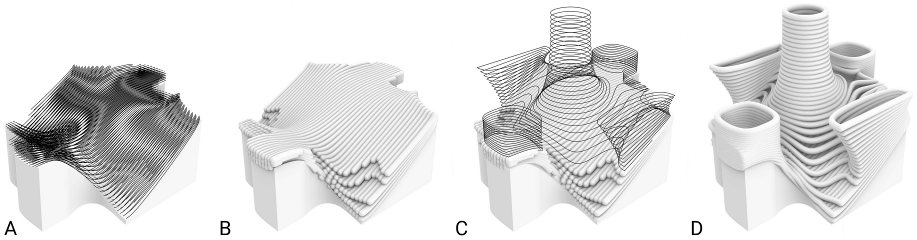

Figure 9: A. 5 base layers toolpathing visualisation; B.Thickness added to the paths; C. Vertical concentric toolpathing visualisation; D. Thickness added to the paths.

4.3.3. Simulation for Dual-Arm Robotic Fabrication

The culmination of our pre-processing stage is the establishment of a dual-arm robotic fabrication workflow. This advanced system, coordinated through Grasshopper, effectively employs our two Universal Robot 10e arms to execute consecutive actions. One arm extrudes the materials to create the facade panel of our block. Once completed, the other arm removes the extruded parts from the support structure on the workbench and places them on an organiser rack, allowing the extruding arm to resume its work. This collaborative approach accelerates production by minimising human intervention and streamlines panel organisation for the final wall assembly (Fig. 10).

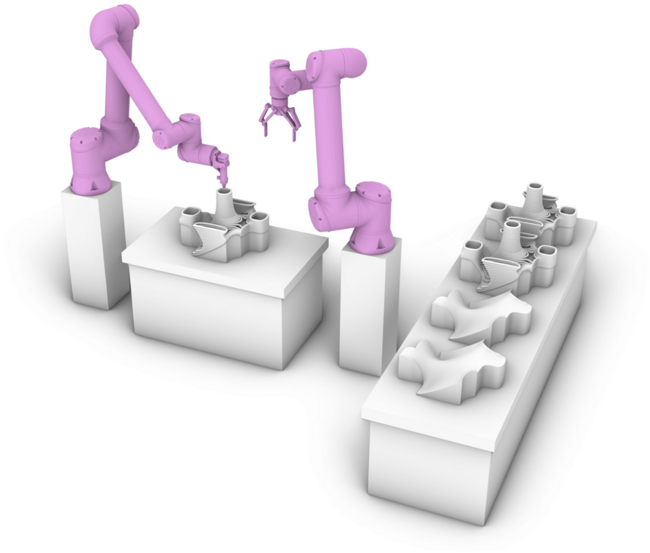

Figure 10: A dual-arm robotic system in action, highlighting the sophisticated choreography between extrusion and assembly in the fabrication of the designed blocks.

5. Discussions of Results

The method workflow was tested at each phase and the connection of its components (parametric design, environmental simulation, and post-processing and simulation for robotic fabrication). The resulting design of the modular block shows promising results in thermal regulation. Collectively, the resulting workflow is applicable to other designs and to different scales. Further experimentation in interpreting the vernacular strategy of the Badgir system can lead to different results. Additionally, our next phase involves materialising the prototype following a robotic fabrication process and testing the physical panel properties.

This robotic fabrication workflow was formulated as an applicable method for other designers to follow. Importantly, the workflow facilitates the incorporation of discrete tasks of passive design, environmental simulation and design processing for fabrication into a successful design framework. The importance of our proposed method lies in testing a feasible design workflow driven by a passive design strategy, with the aim of encouraging other designers to follow and achieve ecologically-conscious design prototypes.

6. CONCLUSIONS AND FUTURE WORK

In conclusion, our research serves as an attempt to guide designers to adopt the intersection of low-tech environmental solutions with advanced computation, to contribute to the paradigm shift towards ecologically driven design methods. Combining traditional architectural wisdom with advanced technologies, the research method involved experimentation and exploration, computational modelling, and rigorous environmental simulations, all integrated into a design process aimed at a higher environmental performance. Future work involves investigation of natural materials for prototyping the windcatcher modular design.

The core of our research contribution lies in the quest for transitioning from active strategies to passive design principles for mitigating current and future challenges of the need for decarbonization and environmental efficiency. Although still in-progress, the work presents a feasible method to embed passive environmental strategies and how to prepare such design for robotic extrusion. Our next task involves the fabrication phase and testing procedures. The method workflow will be shared publicly as an open-source accessible framework for designers to use.

References

Abdelmohsen, S., Adriaenssens, S., El-Dabaa, R., Gabriele, S., Olivieri, L., & Teresi, L. (2019). A multi-physics approach for modeling hygroscopic behavior in wood low-tech architectural adaptive systems. *Computer-Aided Design, 106,* 43-53. https://doi.org/10.1016/j.cad.2018.07.005

Antonini, E., Boeri, A., & Giglio, F. (2020). Beyond Emergency Towards Circular Design: Building Low Tech. In *Emergency Driven Innovation: Low Tech Buildings and Circular Design* (pp. 59-86). Cham: Springer International Publishing.

Belmonte, M.-V., Díaz-López, C., Gavilanes, J., & Millán, E. (2021). Introducing passive strategies in the initial stage of the design to reduce the energy demand in single-family dwellings. *Building and Environment, 197,* 107832. https://doi.org/10.1016/j.buildenv.2021.107832

Caetano, I., & Leitao, A. (2020). Architecture meets computation: an overview of the evolution of computational design approaches in architecture. *Architectural Science Review, 63*(2), 165-174.

Chiujdea, R. S., & Nicholas, P. (2020). Design and 3D Printing Methodologies for Cellulose-based Composite Materials. *eCAADe 2020 Anthropologic - Architecture and Fabrication In the Cognitive Age*. https://doi.org/10.52842/conf.ecaade.2020.1.547

Cojocaru, A., & Isopescu, D. N. (2021). Passive Strategies of Vernacular Architecture for Energy Efficiency. *Bulletin of the Polytechnic Institute of Iași. Construction. Architecture Section, 67*(2), 33-44. https://doi.org/10.2478/bipca-2021-0013

Kolarevic, B., & Malkawi, A. (2005). *Performative architecture: Beyond Instrumentality*. Routledge.

Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings, 40*(3), 394-398. https://doi.org/10.1016/j.enbuild.2007.03.007

Yazici, S., & Tanacan, L. (2020). Material-based computational design (MCD) in sustainable architecture. *Journal of Building Engineering, 32*, 101543. https://doi.org/10.1016/j.jobe.2020.101543

Yuan, P. F., Zhang, M., & Han, L. (2013). *Low-Tech Digital Fabrication: Traditional Brick as Material in Digital Practice*, Berlin, Heidelberg.

Liu, M., Nejat, P., Cao, P., Jimenez-Bescos, C., & Calautit, J. K. (2024). A critical review of windcatcher ventilation: Micro-environment, techno-economics, and commercialisation. *Renewable & Sustainable Energy Reviews*, *191*, 114048. https://doi.org/10.1016/j.rser.2023.114048