THE AM ENVELOPE

A mono-material façade element with complex geometries for structural and thermal performance produced by additive manufacturing
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ABSTRACT
Growing concern about resource consumption in the construction industry has brought new challenges to the design of façades. Compared to traditional techniques, AM stands out for the possibility of fabricating complex geometries embedding multiple functions. This study explored how the potentials of Fused Deposition Modelling can be used to create a multifunctional façade element for thermal insulation and structural stiffness. Physical testing and software simulations have been performed to assess the properties of complex geometries and retrieve design guidelines. A digital workflow was developed, encompassing performance-driven design, performance assessment and geometry generation for fabrication. The study highlights how, by manipulating porosity and material distribution, it is possible to design stiff, insulating envelope components which are suitable for manufacturing with FDM using polymers.

KEYWORDS
Additive Manufacturing - Thermal Insulation - Topology Optimisation - Façade - Digital design
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CHAPTER 01 - INTRODUCTION

This chapter presents the topic of the research, focusing on the background of the study and its relevance in the built environment. The possibility of additive manufacturing for the design of building envelope components are highlighted and the scope of the study is presented. Finally, the structure and the methodology of the research are described.
1.1 Resource and Energy consumption in the Building Industry

Buildings and construction industry together account for 36% of global final energy consumption and 39% of energy-related carbon dioxide (CO2) emissions (UN Environment and International Energy Agency, 2017). Additionally, construction and demolition waste is the most significant waste stream in the EU volume-wise, representing about one third of all waste produced (European Commission, 2016). Growing concern about resource and energy consumption has brought new challenges for the design of buildings.

1.2 The role of the building envelope

The building envelope is in itself one of the most complex parts of the building as its role of separating the outside from the inside requires different performances to be tackled. Recently, new regulations have redefined the role of façades in the overall building concept, with stringent requirements in terms of performance and materials.

Traditional construction techniques rely on the assembly of different components to tackle a specific function. In spite of the great advancements achieved in the façade industry over the last century, with façade elements becoming more and more sophisticated and efficient, there has been little rethinking of the nature of the building envelope (Strauß, 2013). Façade components are considered as arrays of functional layers to which different performances are delegated. With increasing complexity of the systems, reducing material consumption and design for disassembly are major fields of study.

1.3 Possibilities of Additive Manufacturing

After being applied in other fields, additive manufacturing (AM) is currently being investigated for application in the building industry. Compared to traditional manufacturing techniques, AM shows some unique capabilities that suggest potential application for the building envelope:

- Geometrical complexity can be easily achieved so that optimised and customised shapes are possible;
- Material complexity can be achieved by manipulating geometry and hierarchies at the meso-scale so that the material can be designed to obtain different properties were needed;
- No additional cost for geometric complexity is required as tooling and expertise of operators are not affected;
- Need for assemblage is reduced as AM enables the production of components integrating different functions within the same material;
- Waste material is reduced as a direct consequence of the additive manufacturing process;

Therefore, AM has the potential for creating mono-material multifunctional façade components with complex geometries to achieve specific performances, without having to rely on the assembly of different layers. This opportunity can revolutionise the concept of building envelope and suggests new ways to design and regard façades (Figure 2).

![Figure 1: Façade as array of functional layers. Source: http://www.fatfacades.co.uk](image1)

![Figure 2: Requirements of façades according to Knaack, own elaboration from Klein (2015)](image2)
1.4 Problem statement

From the scientific community and industries, existing research on AM for the building envelope has proved to be promising in two main directions and at two different scales:

- The design of topologically optimised structural connections for load transfer (Figure 3);
- The design of multi-functional façade panel with complex geometries at meso-scale for climate control (Figure 4);

Among the key requirements of the building envelope, thermal and structural performance are the most promising aspects to be investigated as both can be controlled by the geometry of the component and both can contribute to savings in terms of material and energy consumption. In particular, thermal insulation is a property which is strongly related to the geometry of the problem and different thermal conductivity values can be achieved with the same material by changing its structure. At the same time, providing stiffness to resist wind load and supporting self-weight are primary requirements for the façade which can be addressed by studying the structural problem and placing material where needed, following the flow of forces and thus overcoming material limitations.

How structural and thermal performances can be addressed using complex geometries and integrated in a mono-material façade panel created by AM is still to be investigated.

1.5 Research Questions

According to the problem statement described above and considering the capabilities of additive manufacturing for application in the building envelope, the main research question is formulated as follows:

How can the potentials of additive manufacturing be used to create a multi-functional façade panel with complex geometries for optimal thermal insulation and structural stiffness, making efficient use of material?

Considering the need to address non-standard geometries to obtain enhanced performance, the research sub-question is as follows:

What is geometrical and material complexity? How can the thermal and mechanical properties of complex geometries be assessed?

According to the need to investigate additive manufacturing as a production technique, some sub-questions are formulated:

Which materials, among the ones that can be used in AM, are most suitable for producing an envelope component for thermal insulation and structural stiffness?

How can a façade component be processed with AM? What are the different production techniques and their limitations related to the complex geometries?

In relation to the proposed building envelope design and the targeted integration of performance, the following sub-question are formulated:

What strategies can be adopted to design complex geometries tackling structural and thermal performance in a façade component?

What is the optimal geometry for the component to achieve structural stiffness? Which tools or procedures are best suited to design it?

What is the optimal geometry for the component to achieve thermal insulation? Which tools or procedures are best suited to design it?

Considering the need to use computational design tools in orders to handle geometrical complexity and aid the proposed AM fabrication, the following sub-questions are addressed:

How can digital tools aid the design of the proposed façade component?

How can the optimal geometries be developed to create the proposed façade component?
1.6 Research Objective

According to the research questions, the research objective is formulated as follows:

The design of a mono-material multifunctional façade panel in which geometry is optimised for thermal insulation and structural stiffness. This façade panel will be able to tackle different requirements, making optimal use of material and reducing the time needed for assembly. A prototype will be manufactured to show the feasibility of the production with AM.

Figure 5: Concept for AM envelope

1.7 Research Structure

The methodology for this thesis will be a combination of research through design and performance-based design.

The research will develop through the following stages:

1. Foundation knowledge
   A literature review is performed to gain insight on:
   • Additive Manufacturing (process workflow, materials, techniques, component scale, application for the building envelope);
   • Geometrical Complexity (Cellular structures and lattices, thermal properties, mechanical properties);
   • Relation between structural performance and geometry: Topology Optimisation (definition, method, combination with AM; challenges, case studies, tools);
   • Relation between thermal performance and geometry: (micro-structure of insulation materials, case studies, tools);

2. Design Boundaries
   According to the outcomes of the literature research, the boundary conditions for the design are defined in relation to material choice, production process, component scale, target thermal performance, target structural performance, geometries to explore, workflow and design environment.

3. Research through design exploration
   This phase entails the exploration of geometries in relation to their structural and thermal performance. The different options will also be evaluated considering the production with AM. The geometries will be digitally modelled, working in the same parametric environment to have a better control over the relation between design variables and required performances. The parametric environment of Grasshopper plug-in for Rhino will be used. Crystallon is a Grasshopper plug-in that will be used to generate solid cellular structures within a design space.

   The assessment of the designs will be done by means of physical testing and digital tools. In particular, digital tools will be used for the optimisation of the structure using Topology Optimisation and to assess the structural performance of the optimised geometry. Specific design limitations/targets deriving from the AM production will be considered in the optimisation process. TO will be performed within the Grasshopper environment. Plug-ins such as Millipedes will be used. In the preliminary design phase, a benchmarking among different tools on speed, robustness, functionality and flexibility will be done to evaluate the best option.

   Samples will be produced using AM techniques. In this context some important aspects will be explored: dimensional accuracy and tolerances, handling of the geometry and information transfer, slicing of the geometry, need for infill/support structure, printing time, surface quality. Physical testing will be used to assess the thermal performance of the 3D-printed samples. Experiment will be set-up to assess the thermal resistance of the sample by measuring the heat flux under an induced temperature difference using thermocouples and sensors. The results will be compared with simple analytical models and software simulations in order to test the reliability of the calculation methods and assess the option to be integrated in the design workflow.

   Simulations of the thermal performance will be done using external software tools to the parametric environment like Trisco and Comsol. Depending on the specific geometry to be tested, the best tool will be evaluated.

4. Component design
   According to the findings of the design exploration, a façade panel integrating the optimised geometry will be designed with focus on: geometry and material distribution within the panel, assembly and relation to building structure, definition of a façade system, validation of structural and thermal performance. Moreover, in this context, a digital workflow will be proposed to be used as tool to generate envelope components according to performance-driven guidelines.

5. Prototyping
   A prototype will be built to test the feasibility of the production by additive manufacturing. Results from the production of the samples for testing in phase 3 will be taken into account and use as guidelines for the production.

References:


1. What is geometrical and material complexity? How can the thermal and mechanical properties of complex geometries be assessed?

2. Which materials, among the ones that can be used in AM, are most suitable for producing an envelope component for thermal insulation and structural stiffness?

3. How can a façade component be processed with AM? What are the different production techniques and their limitations related to the complex geometries?

4. What strategies can be adopted to design complex geometries tackling structural and thermal performance in a façade component?

5. What is the optimal geometry for the component to achieve structural stiffness? Which tools or procedures are best suited to design it?

6. What is the optimal geometry for the component to achieve thermal insulation? Which tools or procedures are best suited to design it?

7. How can digital tools aid the design of the proposed façade component?

8. How can the optimal geometries be developed to create the proposed façade component?
This chapter introduces all the relevant literature which has been consulted in this study to gain insight on the main focuses of the research. First, the concept of material and geometrical complexity is explored and thermal and structural properties of such geometries are presented. Then, additive manufacturing techniques and materials are reviewed and assessed in relation to application to the proposed façade design. Finally, the relation between performance and geometry is addressed by analysing case studies and exploring different strategies aimed at the enhancement of the performances.
2.1 GEOMETRY AND MATERIAL COMPLEXITY

Materials with a spatially varying complex structure can easily be observed in nature. In the evolution of biological forms, material, shape and structure are interrelated and responsible for the performance of an element. Natural elements such as wood, coral and cancellous bone exhibit complex material structures which vary in space to better respond to the functional requirements. The micro-structure of such materials is hierarchically organised and intended to serve multiple functions. Such material can be referred to as functionally graded materials (FGMs) in which thermal, electrical and structural properties vary in the structure according to the required performance. While homogeneity is preferred in industrially fabricated structures to ease the production process and multifunctional requirements of a component are tackled by different elements assembled together, natural structures show how geometrical complexity allows for the creation of multifunctional high-performance material structures. Engineers have been studying and designing such material structures for a long time in order to build lightweight structures with specific functionalities.

2.1.1 Designing cellular structures

A solid material can be transformed in a cellular solid by designing its micro-structure. In this way, the single-valued properties of the material can be vastly extended (Ashby, 2006). The properties are influenced by mainly three factors:

- material: properties of the solid of which the cellular structure is made of;
- topology: the shape of the cells and their connectivity;
- porosity of the material: defined as $(1 - \rho_{\text{cell}} / \rho_{\text{solid}})$ where $\rho_{\text{cell}}$ is the density of the cell and $\rho_{\text{solid}}$ is the density of the solid of which it is made.

Cellular solids are composed of a typical cellular structure, with different possible degrees of symmetry. Honeycomb structures, meshes, foams and lattices are characterised by different unit cell type. The cell can be a strut-based member or a surface-based member: the former can have variations according to number and orientation of the struts, the latter can vary depending on the geometry of the surface and the connection between cells so that open or closed cell structures exist.

The topology of strut-based cellular structures can be defined by referring to the concept of Bravais Lattice. In crystallography, a Bravais Lattice is defined as an array of points generated by a set of translations in a 3-dimensional space. The lattice can be generated by three unit vectors a set of integers so that each lattice point, identified by a vector $r$, can be obtained from the following expression:

$$ r = k \cdot a_1 + l \cdot a_2 + m \cdot a_3 \quad [1] $$

where:
- $k$, $l$ and $m$ are a set of integers;
- $a_1$, $a_2$ and $a_3$ are the unit vectors in the three directions.

In 3D, 14 different lattice structures are defined according to the magnitude of the unit vectors and the angles between them. Additional variations of these configurations can be obtained by combining the primitive typology with the one of the centering types. Centering types identify the position of lattice points in the unit cell and further define the porosity of the cell and its structural behaviour (Figure 6). By manipulating the crystal systems and the centering types, different cell structures can be generated. Typical lattice cell configurations are shown in Figure 7.

Surface-based cellular structures can be made of closed or open cells. In the simplest case, open cell structures are characterised by presence of bulk material at the edges of the cell, while closed cell structures are delimited by thin walls. Engineers have been studying the topology of surface-based cellular structures for a century. A main field of research is the definition of geometries in which, subject to some constraints, the total surface area is minimized. Such geometries are called minimal surfaces. Minimal periodic surfaces (that repeat their structure in 3 dimensions) have been studied and mathematically defined as:

$$ f(x,y,z) \leq t \quad [2] $$

where:
- $x$, $y$, $z$ are variables;
- $t$ is the isovalue governing the offset for the level-set;

Among the most investigated geometries are Schwarz primitive, Schwarz’s Diamond and Schoen’s Gyroid which have widely been used to design nanostructures with high volume to surface ratio and porosity (Figure 8). Another example of minimal surface is the Weaire-Phelan structure. This is a bubble foam structure that was created to answer to the so called Kelvin problem: “How can space be partitioned into cells of equal volume with the least area of surface between them?”. The Weaire-Phelan structure is a polyhedral foam which uses two kind of cells to fill the space: an irregular dodecahedron and a tetrakaidecahedron (Figure 9).
2.1.2 Mechanical properties of cellular structures

The main difference in mechanical properties between foams (surface-based cells) and lattices (strut-based cells) is the deformation behaviour. According to Ashby (2005), foams are bending dominated structures while triangulated lattices are stretch dominated structures. This distinction can be made following Maxwell’s stability criterion, according to which a cellular structure can be considered as pin-jointed frame of struts and frictionless joints (Figure 10). The condition for the structure to be statically and kinematically determined is:

\[ M = b - 3j + 6 = 0 \]  \[ (3) \]

where:
- \( b \) is the number of struts;
- \( j \) is the number of frictionless joints;

If \( M > 0 \), the structure has one or more degrees of freedom and no stiffness or strength on the direction of the allowed displacement. Since the joints of cellular structures are considered rigid, the struts will bend under loading. If \( M = 0 \), the structure is said to be stretch-dominated. When loaded, the struts would carry the load by means of tension and compression. If \( M > 0 \), the frame structure is over-constrained and the struts carry tension or compression even if no external load is applied. In other words, they are in a state of self-stress.

![Figure 8: Schwarz Primitive surface, Schwarz Diamond surface and Schoen Gyroid. Source: https://en.wikipedia.org/wiki/Schwarz_minimal_surface](image1)

![Figure 9: Weaire-Phelan structure consisting out of irregular dodecahedrons in yellow and tetrahexadraedra in gray. Source: Buffel et al. 2014](image2)

![Figure 10: Pin-jointed frames: (a) is bending dominated, (b) is stretch dominated, (c) is over-constrained. Source: Ashby, 2006](image3)

Triangulated geometries are stretch-dominated structures. Typical polyhedral structures of foams are bending-dominated as the Maxwell’s criterion equation results in a negative number. The combination of different polyhedral structure can, however, result in a stretch-dominated frame, like for example the combination of tetrahedron and octahedron. In general, lattice structures are more structurally efficient than foams as the load transfer does not include bending but only tension and compression. Open cell foams face bending of the edges when loaded while closed foams tend to buckle because of their thin edges. For this reason, strut-based cellular structures, such as lattices, are widely used in engineering application when lightweight and structural performance are required.

Ashby (2006) provides the stress-strain curve for a bending dominated material (Figure 12). The material structure shows a linear elastic behaviour, with Young’s Modulus \( E_{\text{cell}} \), until a point where plastic yielding or fracture of buckling occur. Then, the structure continues to collapse at a constant stress state, the plateau stress, until opposite sides of the cell collapse into each other and, with the densification of the structure, the stress increases. Gibson & Ashby (1997) demonstrated that the relative Young’s modulus, \( \frac{E_{\text{cell}}}{E_{\text{solid}}} \), of bending-dominated structures scales with the relative density to the power of two, \( \left( \frac{\rho_{\text{cell}}}{\rho_{\text{solid}}} \right)^2 \). The relative yield strength, \( \frac{\sigma_{\text{cell}}}{\sigma_{\text{solid}}} \), is proportional to \( \left( \frac{\rho_{\text{cell}}}{\rho_{\text{solid}}} \right)^{3/2} \).

For lattice structures with stretch-dominated behaviour, Gibson & Ashby (1997) provide a conservative expression to estimate the mechanical properties. Considering that, under a certain load case (direction of load), at least \( 1/3 \) of the structure will be carrying tension or compression, the relative Young’s Modulus can be approximated to \( 1/3 \) of the relative density:

\[ \frac{E_{\text{cell}}}{E_{\text{solid}}} = \left( \frac{\rho_{\text{cell}}}{\rho_{\text{solid}}} \right)^{1/3} \]  \[ (4) \]

With the same principle, the elastic limit that can be reached by plastic yielding can be approximated like:

\[ \frac{\sigma_{\text{cell}}}{\sigma_{\text{solid}}} = \left( \frac{\rho_{\text{cell}}}{\rho_{\text{solid}}} \right)^{1/3} \]  \[ (5) \]

As can be seen by the stress strain curve, stretch dominated structures show a linear elastic behaviour until the elastic limit with a much greater modulus and strength than bending-dominated structures with same relative density. After reaching plastic buckling or brittle fracture, depending on the slenderness of the structure and on the material, the structure undergoes a phase of post-yielding softening before densification.

Figure 14 and 15 provide an overview of the behaviour of bending-dominated and stretch-dominated structures in terms of stiffness and strength. The ideal behaviour in stiffness for bending-dominated structure is exhibited by woven structures, while the behaviour of foams usually falls below the line as their structure is often heterogeneous due to the manufacturing process. This indicates that AM production
of foams could improve its theoretical mechanical performance by ensuring a more homogeneous configuration. Ideal stiffness for stretch-dominated structure is exhibited by honeycombs, when loaded parallel to the axis of the hexagon. As regards strength, woven structures are ideal among bending dominated structures. Among stretch-dominated ones, honeycombs fall below the ideal line as the thin walls are likely to buckle while pyramidal lattices and the so called Kagome lattices show an ideal behaviour.

All things considered, the following design principles can be retrieved. For structural application in which strength, stiffness and light weight is required, stretch- dominated lattices are to be preferred. Honeycombs and pyramidal lattices are a good choice. The deformation at plateau stress of bending-dominated structures makes them suitable for applications in which energy absorption is required.

2.1.4 Thermal properties of cellular structures

When it comes to heat flow in cellular structures, different approaches can be followed to estimate the thermal performance. Cellular and lattice structures are two-phase materials in which the contribution of the solid part and that of the void part to the thermal resistance can be considered separately and added up. Commonly used insulating materials are porous and take advantage of the low thermal conductivity of still air. Such structures are characterised by a complex heat flow where all three modes of heat transfer take place: conduction through the solid phase and the enclosed gas, convection within the cells and radiation through the cell walls and voids (Figure xx). This heat flow can be described by an effective thermal conductivity $\lambda$.

Generally speaking, the heat transfer for a wall element can be calculated as:

$$ q = \frac{\Delta T}{R_{tot}} \quad \text{[W/m²]} \quad \text{(6)} $$

where:
- $\Delta T$ is the temperature difference between inside and outside;
- $R_{tot}$ is the sum of the specific thermal resistance of the layers of the wall, the resistance of the outside surface and that of the inside surface.

The resistance of each layer is the sum of the contributions of the three modes of transfer through a medium: conduction, convection and radiation. Among the three modes of heat transfer, some assumptions can be made to simplify the model:

- Heat transfer by convection does not occur with small air voids/cavities. If the size of the cell is kept within 10 mm air does not move and convective air movements do not happen. For cellular structures convection can be reasonably neglected.
- The cell geometry attenuates the heat transfer by radiation via absorption and scattering. In case of open cell structures or lattice structures radiation is negligible at room temperature, as shown in Rossland equation:
  
  $$ \lambda_{rad} = \frac{(16 \cdot \sigma \cdot T^3)}{3 \cdot K} \quad \text{(7)} $$

where:
- $\sigma$ is the Stefan Boltzmann constant ($5.670367 \times 10^{-8}$ W·m$^{-2}$·K$^{-4}$);
- $T$ is the absolute temperature (K);
- $K$ is a factor depending on the density of the solid and the cellular structure, the cell dimension, the fraction of solid in a strut and the extinction coefficient;
Conduction through solid material and air is the main mode of heat transfer in cellular structures. On a first approximation, the thermal properties of a cell can be estimated using the rule of mixtures, considering its solid and gas composition:

\[ \lambda_{\text{cell}} = \lambda_s V_s + \lambda_g V_g \]  

(8)

where:
- \( \lambda_s \) is the thermal conductivity of the bulk material [W/m\(\cdot\)K];
- \( \lambda_g \) is the thermal conductivity of the gas part [W/m\(\cdot\)K];
- \( V_s \) is the volume of the bulk material [m\(^3\)];
- \( V_g \) is the volume of the gas part [m\(^3\)];

However, this expression does not take into account the influence of the internal geometry on the thermal performance of a cellular structure. Ashby (2006) derives an expression to describe the thermal conductivity in relation to the porosity, assuming that 1/3 of the struts of the cellular structure are parallel to one Cartesian axis:

\[ \lambda_{\text{cell}} = \frac{1}{3} \left( \frac{\rho_{\text{solid}}}{\rho} \right) \lambda_s + \frac{2}{3} \left( \frac{\rho_{\text{solid}}}{\rho} \right)^2 \lambda_g \]  

(9)

where:
- \( \lambda_s \) is the thermal conductivity of the bulk material [W/m\(\cdot\)K];
- \( \lambda_g \) is the thermal conductivity of the gas part [W/m\(\cdot\)K];
- \( V_s \) is the volume of the bulk material [m\(^3\)];
- \( V_g \) is the volume of the gas part [m\(^3\)];

Where the first term describes the heat flow through cell edges or walls while the second term describes the contribution of the gas contained in the cell. This approximation ceases to be valid for high density foams where the joints occupy a larger fraction of the volume. So the following expression should be used instead:

\[ \lambda_{\text{cell}} = \frac{1}{3} \left( \frac{\rho_{\text{solid}}}{\rho_s} \right) \lambda_s + \left[ 1 - \left( \frac{\rho_{\text{solid}}}{\rho_s} \right) \right] \lambda_g \]  

(10)

where:
- \( \lambda_s \) is the thermal conductivity of the bulk material [W/m\(\cdot\)K];
- \( \lambda_g \) is the thermal conductivity of the gas part [W/m\(\cdot\)K];
- \( \rho_s \) is the density of the bulk material [kg/m\(^3\)];
- \( \rho_{\text{cell}} \) is the density of the gas part [kg/m\(^3\)];

which correctly reduces to \( \lambda_{\text{cell}} = \lambda_{\text{solid}} \) when \( \rho_{\text{cell}} = \rho_{\text{solid}} \). Nevertheless, this formula is valid only for certain cell topologies, where 1/3 of the struts lies parallel to each Cartesian axis and results in a very conservative outcome.

The problem of cell topology and finding an expression that could be applied to any case have been investigated. Several analytical models have been developed to describe the thermal conductivity of a cellular structure in terms. Hegman (2018) proposes a model which analyses the problem in terms of two limiting cases, the “parallel and series” arrangement of the solid and gaseous constituents.

First, the porosity of the cell can be defined as:

\[ p = \left( \frac{V - m}{V} \right) = 1 - \frac{\rho^*}{\rho} \]  

(11)

where:
- \( V \) is the volume [m\(^3\)];
- \( p \) and \( \rho^* \) are the solid and foam density, correspondingly [kg/m\(^3\)];

The parallel and series cases are then described as follows:

\[ \lambda_{\text{parallel}} = p \lambda_{\text{gas}} + (1 - p) \lambda_{\text{solid}} \]  

(12)

\[ \lambda_{\text{series}} = \frac{\lambda_{\text{solid}} \lambda_{\text{gas}}}{p \lambda_{\text{solid}} + (1 - p) \lambda_{\text{gas}}} \]  

(13)

where:
- \( \lambda_{\text{solid}} \) is the thermal conductivity of the solid material [W/m\(\cdot\)K];
- \( \lambda_{\text{gas}} \) is the thermal conductivity of the gaseous component [W/m\(\cdot\)K];
- \( p \) is the porosity defined in (6).

The two models can be combined to give an overall thermal conductivity. Hegman (2018) proposes two different methods. One considers superposition of the two aspects as:

\[ \lambda = A \lambda_{\text{parallel}} + (1 - A) \lambda_{\text{series}} \]  

(14)

where \( A \) is the fraction of heat transfer in the parallel model.

The other considers the final conductivity as the square root of the sum of the contribution of the two limiting cases squared:

\[ \lambda = \sqrt{A \lambda_{\text{parallel}}^2 + (1 - A) \lambda_{\text{series}}^2} \]  

(15)

Figure 16: Parallel and series arrangement of the solid and gaseous constituents in cellular structures
Another expression is proposed by Leach (1999) which unifies the results of a number of approaches to calculate the conductivity of a cellular structure, considering its density and the properties of its component phases. The combined expression takes into account four different formulations of the problem: parallel model, series model, cubic cells models, spherical pores, and can be written as:

$$\lambda_{\text{cell}} = \frac{2}{3} \left( \frac{\rho_s}{\rho_c} \right) \lambda_s + \lambda_g$$  \hspace{1cm} [16]

where:
- $\lambda_s$ is the thermal conductivity of the bulk material [W/mK];
- $\lambda_g$ is the thermal conductivity of the gas part [W/mK];
- $\rho_s$ is the density of the bulk material [kg/m$^3$];
- $\rho_c$ is the density of the gas part [kg/m$^3$];

This expression is very close to the formulation given by Ashby, Gooskens (2016) provides a comparison of different expressions to calculate the thermal conductivity of cellular structures and points out how the result vary in a large range, making it difficult to choose a method based on validity and reliability.

Depending on topology and dimension of the body to be studied, the problem could be studied according to the model provided in NEN EN ISO6946 standard which provides calculation methods for thermal resistance and transmittance of building components. In particular, the standard presents a calculation method for thermal transmittance of components made up of different layers and annex B presents a method for calculating the resistance of small unventilated airspaces with a width (parallel to the heat flow direction) less than 10 times their thickness.

The resistance of the airspace can be calculated summing the contributions of convection/conduction heat transfer coefficient and the radiation heat transfer coefficient:

$$R_g = \frac{1}{h_a + h_r}$$  \hspace{1cm} [17]

where:
- $h_a$ is the conduction/convection coefficient given in Table 1 for different directions of the airflow.
- $h_r$ is the radiative coefficient,

$$h_r = \frac{h_r(0) \varepsilon_{1} \varepsilon_{2}}{\left[ 1 + \frac{1}{\varepsilon_{1}} - \frac{2}{\varepsilon_{2}} - \frac{2}{1 + \sqrt{1 + \frac{d^2}{l^2} b^2 - d l b}} \right]}$$  \hspace{1cm} [18]

The formula takes into account the geometry of the air space with $d$ being the thickness and $b$ being the width of the airspace. $\varepsilon_1$ and $\varepsilon_2$ are the hemispherical emissivities of the surfaces on the warm and cold faces of the airspace. $H_0$ is the radiative coefficient for a black-body surface which varies according to the temperature, as given in Table 2:

<table>
<thead>
<tr>
<th>Mean temperature (°C)</th>
<th>$H_0$ (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>4.1</td>
</tr>
<tr>
<td>0</td>
<td>4.6</td>
</tr>
<tr>
<td>10</td>
<td>5.1</td>
</tr>
<tr>
<td>20</td>
<td>5.7</td>
</tr>
<tr>
<td>30</td>
<td>6.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Direction of heat flow</th>
<th>$h_a$ (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>1.25</td>
</tr>
<tr>
<td>Upwards</td>
<td>1.55</td>
</tr>
<tr>
<td>Downwards</td>
<td>0.12 + 0.544</td>
</tr>
</tbody>
</table>

$^*$ Or: $Fayer: (0.85b)$

Tenipierik and Cauberg (2007) developed a calculation model which looked into the effect of a thermal bridge at the edge of vacuum insulation panels. This set of equations was also used to describe the effect of point-like thermal bridges, for spacers inside double glass. The same model could be used to describe the thermal resistance of cellular structures, assuming that the thermal resistance is provided by the gaseous part and the solid material acts like a thermal bridge. The effective thermal conductivity of 1 layer of cells can be estimated and a way to convert the model for multiple layers of cells should be found.

Overall, the study of the thermal performance for cellular structures is a complex problem, highly dependent on the geometry of the object being analysed. Therefore, the results from the analytical models should be compared and verified with numerical analysis and physical experiments to assess their reliability.

References:


2.2 ADDITIVE MANUFACTURING

2.2.1 Process

Additive manufacturing is a relatively new production technique that is suggesting a revolution in the way products are designed, manufactured and distributed to the end users (Gao et al., 2015). The process has already been implemented in various industries, at first in high-value adding sectors such as aeronautical and biomedical industries. However, over the last years, new applications are being proposed along with materials and processes being constantly redefined. Growing interest in this new technology is linked to the reduced cost and availability of programmable controllers and CAD software that have somehow democratised the design process. It comes as no surprise that one of the main drivers for the development of this technique have been industries that rely on prototyping in early stage of the product design. Going beyond the prototyping, AM technologies can have a great impact on traditional assembly, assembly process and supply chain. Additionally, this new manufacturing technique is considerably affecting the end-customers, by redefining their role in the production systems and offering the possibility to take partake in the design process through new available platforms and to create highly customised products.

AM processes are techniques for fabricating geometries from three-dimensional model data. The process consists of printing successive cross sectional layers of an object on top of each other (Ngo et al., 2018). As a general rule, the different production processes consist of a number of steps (Figure 17), where there is a direct data transfer from computer geometry generation and production. The phases on additive manufacturing process can be described as follows:

- The production process starts with a 3D solid model, modelled through CAD technology.
- In order to transfer the geometrical information to the production software the model is translated into the STL (Standard Triangulation Language) file format. In this file format, the solid geometry is discretized and tessellated into a series of facets, whose number define the accuracy of the representation.
- The model is then sliced into a number of layers with predetermined thickness by an interface software. In this phase a g-code for the machine is generated with settings for the machine such as extrusion width, speed, layer dimension, infill pattern and percentage.
- When the machine has received the STL file and the g-code, each layer is created via selective deposition of material to form the object.
- The product undergoes post-processing such as cleaning, curing and finishing. According to the application, the products can be post-processed such as UV coatings.

Over the last years, application of additive manufacturing to big-scale components has suggested the use of robotic manipulators. Contrary to traditional processes, AM combined with robotics allows for manufacturing “outside the box”, overcoming limitations to the build workspace derived from machines (Danielsen Evjemo et al., 2017). Robotic additive manufacturing requires a different process phase for toolpath planning and design. Complexity can increase when different printing directions are combined (Figure 18).

The uptake of AM in the building sector has been slow and limited, despite the great advantages offered. Wholer’s report (2017) states that architectural applications account for just 3% of the total AM industry. This could be explained by the inherent predilection for cost-effective solution in the construction industry rather than for high-performance expensive products. However, promising potential has been shown by recent projects applying large-scale AM for building components.

Automated building construction with 3D printing can lead to a significant reduction in construction time and man power (Gao et al., 2015). At the same time this production technique can be utilised in all those areas where geometric complexity needs to be achieved along with specific performances, with several advantages compared to tradition manufacturing techniques. In particular, when compared to subtractive manufacturing techniques, such as cutting, milling and grinding, AM processes shows a series of advantages for production in Architecture that suggest specific field of research and future developments:

- **Design flexibility** at different scales
  - Geometrical complexity: The layer-to-layer fabrication enables the creation of any complex shape since there is no need for tools to be able to reach deep zones nor to accommodate fixtures. Coupled with digital design, AM is able to process complex geometries that have been topologically optimised for a given performance.
  - Material complexity: With the same principle, material complexity can be achieved by manipulating geometry, hierarchy and size scales. The meso-structure of the material can be designed to obtain different properties were needed. Functionally graded material can be created with complex material composition and property gradients in a single component, enabling the creation of multifunctional components.

- **Cost of geometric complexity**: The complexity comes at no additional cost since additional tooling is not required and the expertise of the operators does not need to increase.

- **Need for assemblage**: While the production of complex elements is usually achieved by assembly of different elements together, AM enables the production of mono-material components. It is also very easy to integrate different functions in the same component with single-part assemblies that feature mechanisms.

- **Time and cost efficiency**: Geometrical complexity is traditionally achieved with moulding processes which require high start-up costs and become more cost-effective with large production batches. While generally being more time-consuming, AM processes have no start-up tooling required so that small volume production is as efficient as large volume. This also means that customised and on-demand products become a possibility.
of the component can play an important role for achieving the structural performance and making optimal use of the material, located it where needed. Creating a comfortable interior climate entails ensuring a comfortable temperature by controlling radiation, energy losses and air exchange rates, as well blocking unwanted noise. Both thermal and acoustic insulation can be achieved by controlling the geometry of the component. However, thermal insulation looks like the most promising function in terms of contribution to energy savings in the building. Responsible handling in terms of sustainability includes minimising embodied energy, enabling reuse and recycling and storing energy. While the first two are a consequence of the creation of a mono-material multi-functional component, thermal mass can be tackled using geometrical complexity, also depending on the properties of the material being used. Supporting use of the building does not seem to have many possibilities in terms of geometrical complexity. Spatial formation of façade and in general the architectural expression of the building can be tackled using geometrical complexity, also depending on the properties of the material being used. Resource savings. The results of this assessment are show in Figure 18 where the requirements that look most promising are highlighted: thermal performance and structural performance.

Waste material: The additive process in itself does results in a significant decrease in material waste. Only a small amount of material scrap is produced for support structures. Moreover, the integration of different components in a single assembly further reduces the material waste for a given product compared to traditional techniques. According to the advantages described above, AM shows interesting potentials for application in architecture and the built environment, relatively to:

- Creation of optimised components to tackle a specific performance;
- Creation of components with designed material properties, making use of complex geometries;
- Creation of multi-functional components that tackle different performances in a single element;
- Making optimal use of material by reducing waste;
- Allowing for cost-effective production of customised parts in small volumes

2.2.2 AM for the building envelope

Why

The building envelope is in itself one of the most complex parts of the building as its role of separating the outside from the inside requires different performances to be tackled. Moreover, the façade is also the primary interface of the building, playing an important role in terms of architectural value and appearance. In spite of the great advancements achieved in the façade industry over the last century, with façade elements becoming more and more sophisticated and efficient, there has been little or no rethinking of the nature of the building envelope (Strauß, 2013). Façade components are considered as arrays of functional layers to which different performances are delegated.

Besides the basic requirements for the envelope, growing concern about resource and energy consumption in the building industry has brought new challenges for façades in terms of end of life options and performances. Not only does the façade have to fulfil the required performances as efficiently as possible, but it also has to be designed in such a way that material waste is reduced and the components can be disassembled to allow for positive end of life options such as reusing and recycling. As described in Section 2.2.1, AM potentials enable the creation of mono-material multifunctional components with complex geometries for achieving a specific function without having to rely on the assembly of different components.

What

Klein (2015) presents the façade function tree which describes the façade primary functions within the main function of separating and filtering between nature and interior spaces (Figure 19). These are:

- “Create a durable construction”
- “Allow reasonable building methods”
- “Provide a comfortable interior climate”
- “Responsible handling in terms of sustainability “
- “Support use of the building”
- “Spatial formation of façade”

Every category somehow shows room for potential application of AM techniques. Identifying what are the most promising functions and what can be achieved with the geometrical complexity offered by AM is the starting point of this study. Along with this, it should be assessed which aspect is more likely to lead to saving in terms of material and energy. Bearing structural loads is a major function for the façade that should be able to support its self-load and transfer wind loads to the supports. In this, the geometry
How

The potential for application of Additive manufacturing for the building envelope is being explored in different directions. Holger Strauss (2013) describes how AM technology can be transferred to the building envelope and transform it from a mere enclosure component into a smart, dynamic and integrated function zone. As the construction market is asking for bespoke building solutions, the latest innovation in façade design are being applied at the scale of the single building, with customised solutions for specific projects. For this particular application of non-standard components in small production runs, AM seems to be a very suitable production technique.

As already mentioned in Section 1, existing research on additive manufacturing in the building envelope is developing in two main directions and at two different scales:

- Creation of multi-functional façade panels with complex geometries to tackle specific functions (entire façade component);
- Creation of topologically optimised nodes for load transfer (node)

This trends seem to confirm that the structural and the thermal performance are promising field to explore with the possibilities offered by additive manufacturing. However, there is a lack of integration between the two approaches. The structural performance of the aforesaid multi-functional façade panels is taken into account only at the end of the design to verify the overall stability of the component. However, integrating it in the design of the component could lead to defining specific boundaries for the design of the component and an explicit application on buildings. The intention of this research is to take a step towards the integration of these two approaches.

2.2.3 Techniques

From 1987, when the first additive method was sold on the market, different AM methods have been developed to meet the demands of production in different fields, to improve the quality and the properties of the objects (Knaack et al., 2013). The main AM techniques have been investigated following the comprehensive survey provided by Wu et al. (2016).

Stereolithography (SLA)

SLA is one of the earliest AM methods. The model is created in a bath of photopolymer resin (mainly acrylic or epoxy-based) that cures when exposed to UV light. The geometry is traced by a laser light surface layer after layer and the unreacted resin is removed after the printing. High accuracy and resolution can be achieved in the process, which makes it suitable for small scale applications. The drawback is the large production time, the high cost and the limited amount of suitable materials.

Figure 20: SLA process. Source: www.3dhubs.com
Fused Deposition Modelling (FDM)
FDM can be considered as the best example of additive manufacturing method as the material is deposited in layers with no need for curing or gluing. A continuous filament of thermoplastics is heated at the nozzle to reach a semi-liquid state and then extruded on the platform or on top of previous layers where the material cures. Overhangs, undercuts and non-self-supporting parts require a support structure which can be created with a secondary nozzle using a support material. The process results in a stepped contour for the geometry which limits accuracy and finish of the end part. Layer thickness and orientation along with air gaps between layers are the main parameters influencing the mechanical properties of the products. The main benefits of the process are low cost, simplicity of the process and high speed.

Powder Bed Fusion methods
These methods make use of thin layers of fine powders which are deposited on a platform and fused together with a laser beam or a binder. The geometry is build layer after layer and the excess powder is removed and recycled. As the surface finish is porous, the product may require an infiltration with other materials depending on the application. This process is suitable for powders with low sintering (melting) point. Selective Laser Sintering (SLS) is used for polymers and metals for which the laser does not fully melt the powder but allows fusion of the grains at molecular level. Selective Laser Melting (SLM) is used for steel and aluminium and provides for fully melting of the powder, resulting in superior mechanical properties. For powders with a high sintering temperatures, a liquid binder is used. This process is called three-dimensional printing (3DP), which generally produces parts with higher porosity. Powder bed fusion methods are able to produce parts with fine resolution and high surface quality. Moreover, there is no need for support structures as the powder bed itself acts as support for the geometry. The main drawback of the process are high costs and slow speed.

Direct Energy Deposition (DED)
This method is used to process high-performance super-alloys and comprises other processes such as direct metal deposition (DMD), laser solid forming (LENS™), electron beam AM and wire+ Arc AM. In DED a laser or electron beam generates a melting bath on the surfaces of the model and simultaneously melts a feedstock material (powder or wire). The melted feedstock material is deposited on the melted substrate and the two solidify together. The method allows for multiple-axis deposition and multi-material processing. With a high speed and large work envelopes, this method is suitable for large components and ensures optimal mechanical properties.

Inkjet Printing
This method is used for advanced ceramic structures and uses a stable ceramic suspension which is pumped and deposited through the nozzle on the platform in the form of droplets. The droplets, forming a continuous path, solidify either by contact with a cold substrate (wax-based inks) or by liquid evaporation. The process allows for creation of complex geometries but the quality of the product is influenced by the lack of adhesion between layers and coarse resolution.
Contour Crafting (CC)

Similarly to inkjet printing, contour crafting is used to extrude concrete or soil for large scale structures. Along with a computer guided nozzle, the process requires trowels that follow the nozzle and smoothen the geometry and create an accurate finish. The technique is in reality a hybrid process which also involves extrusion/pouring or injection for filling the inner core between extruded surfaces. The nozzle is supported by a crane or gantry. The main advantage of the process is that, provided that the geometry is self-supporting, no moulds are required reducing labour intensity, construction time and material waste. Allowing for more geometrical flexibility is a major field of research for this process.

2.2.4 Materials

The choice of a suitable production process also depends on the material being used. A diverse range of materials can be used in AM, from common use material to advanced composite materials. The feedstock must be provided in a form that is compatible with the specific technology process: filaments, wires, powders, pastes and inks can be used (Bourell et al., 2017).

Since AM was first developed as a rapid prototyping manufacturing technique, polymers are the most commonly used materials (Knaack et al., 2013). Acrylonitrile butadiene styrene (ABS), polyamide (PA), polycarbonate (PC), polyactic acid (PLA), PET and PETG are suitable thermos-polymers to be extruded in filaments. Thermosetting powders such as polystyrene and polyamides, and photopolymer resins are commonly used as well. Due to the relatively low mechanical properties, new composite materials have been developed with fibre reinforcement. Despite the mechanical limitations, the low conductivity of polymers makes them a suitable option for application in the building envelope as insulating materials.

Metals have been extensively used in AM for application in the aerospace and automotive industry. Taking advantage of the minimum material waste and the possibility of manufacturing optimised shapes. Special material mixes are often used, rather than pure metals, including titanium, steel, stainless steel and aluminium. Metal powder AM enables the production of products with high mechanical properties and accurate parts. On the other hand, the high conductivity makes metal suitable for application where heat-exchange function need to be integrated.

A limited number of ceramic materials is nowadays available for AM. At the moment, the use of ceramics is mainly employed in inkjet printing for manufacturing ceramic scaffolds for tissue engineering. Concrete additive manufacturing is used for large-scale application in the building industry. Compared to the other material groups, concrete does not enable for the same geometrical complexity as the processes require larger nozzle sizes. The possibility of using such material as thermal mass and the high compressive strength makes it suitable for application in the building envelope.

Ngo et al. (2018) present a comparative table where the different materials are assessed in terms of benefit, challenges and main application (Table 4). While metal and ceramics are mainly used in advanced industries, polymers and concrete are also applied in the building industry. The main advantages of polymers are cost-effectiveness, the possibility of building complex structures and customised elements, while the main disadvantage is the poor mechanical properties. The benefit of concrete is the possibility of mass-customisation, less labour required and no need for formwork.

Table 3 compares the different techniques according to material, typical application, benefits, drawbacks and dimensional accuracy. While only contour crafting is generally used for structural applications in the building industry, other techniques look promising for application in the building envelope. For metal connection elements powder bed fusion methods can be used to manufacture customised components with complex geometries, making use of the high accuracy and good mechanical properties offered by the process. Moreover, FDM also looks promising for being low-cost, high-speed and simple process, that could be applied at different scales.

Table 3 : A summary of materials, application, benefits and drawbacks of the main methods of AM. Source: Ngo et al., 2018

<table>
<thead>
<tr>
<th>Materials</th>
<th>Main applications</th>
<th>Benefits</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal and alloys</td>
<td>Armoured and Automotive</td>
<td>Multifunctional optimisation</td>
<td>Limited selection of alloys</td>
</tr>
<tr>
<td></td>
<td>Military</td>
<td>Mass-customisation</td>
<td>Horizontal curvature and poor surface finish</td>
</tr>
<tr>
<td></td>
<td>Biological</td>
<td>Reduced material waste</td>
<td>Process assembly components</td>
</tr>
<tr>
<td>Polymers and composites</td>
<td>Additive Manufacturing</td>
<td>Fast prototyping</td>
<td>Poor mechanical properties</td>
</tr>
<tr>
<td></td>
<td>Medical</td>
<td>General purpose</td>
<td>Limited selection of polymers and reinforcement</td>
</tr>
<tr>
<td></td>
<td>Architecture</td>
<td>Customisation</td>
<td>Anisotropic mechanical properties especially in fibre-reinforced composites</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multi-materials</td>
<td></td>
</tr>
<tr>
<td>Ceramics</td>
<td>Chemical and Automotive</td>
<td>Cost-effective</td>
<td>Limited selection of 3D printable ceramics</td>
</tr>
<tr>
<td></td>
<td>Chemical industries</td>
<td></td>
<td>International sourcing and poor surface finish</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Post-processing (e.g. sintering) may be required</td>
</tr>
<tr>
<td>Concrete</td>
<td>Infrastructure and construction</td>
<td>Low material cost</td>
<td>Limited fatigue and poor durability</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Limited number of printing methods and required ceramic material design</td>
</tr>
</tbody>
</table>

Table 4 : A summary of main applications, benefits and challenges of the main materials for AM. Source: Ngo et al., 2018
Gooskens (2016) developed a tool to assess the potential of functionally graded solids for the building envelope. His research explores and assesses the properties of different lattice structures creating a wall component at three different scales, 300 mm-thickness, 150 mm-thickness and 50 mm-thickness. The lattices had same cell topology (octet lattice type) varying in material, porosity and gradient of porosity. These were assessed according to the thermal and structural performance and potential applications for the building envelope were also suggested. His findings are summarised in Table 1. According to his study, polymers are the most promising material group for application where thermal insulation is required along with a good load transfer capacity but cannot be used as load-bearing parts or to create thermal mass.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Potential/Properties</th>
<th>Risk/Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals</td>
<td>Thermal mass for quick heat absorption, strong structural capabilities, high printing resolution and low porosities obtainable.</td>
<td>Risk of thermal bridge due to high thermal conductivity, heavy weight, poor thermal buffer capabilities.</td>
</tr>
<tr>
<td>Polymers</td>
<td>Low thermal conductivity for thermal insulation, light-weight, non-primary load-bearing structural elements.</td>
<td>No use for thermal mass and thermal buffering, high flexibility in structural behaviour.</td>
</tr>
<tr>
<td>Ceramics</td>
<td>Good thermal mass and buffering properties, strong structural capabilities in compression, average thermal resistance performance.</td>
<td>Weak flexural strength, long curing times limiting geometrical design freedom, heavy weight.</td>
</tr>
</tbody>
</table>

Table 5: Potentials and pointers of different AM materials for applications in the building envelope according to Gooskens (2016).

2.2.5 Component Scale

Large-scale AM with concrete

Research interest in employing AM for building and construction has increased exponentially in the past few years. These production techniques have shown their capabilities for producing advanced structures, from nano-scale (e.g. biomedical engineering) to object scale (mass customised products). Applying these techniques to architecture means defining a different scale for the object being manufactured. Full-scale AM for buildings was proved to be feasible in different projects where concrete mixture extrusion was employed. In 2017, China-based WinSun Decoration Design Engineering co. managed to 3D print a 6-storeys apartment building using a mixture of construction waste materials including concrete, fibreglass and sand. In this case, the structure was fabricated offsite with a diagonal reinforced print pattern and then transported to the building site and assembled (Figure 26).

Large-scale AM with polymers

In the same year Apis Cor, a San Francisco-based start-up, 3D-printed a 38 m² house in Russia in 24h. The production technique was Contour Crafting in-situ, using an innovative mobile construction 3D printer combined with an automated mixing and pump system (Figure 27).

Both projects demonstrated that AM for construction can be advantageous in terms of building time, cost and risks related to construction, along with reducing the environmental impact of process and transport. Research towards automation in the building industry is currently focusing on fine-tuning the mix ratios for feedstock and refining/optimising the building systems. The implementation of this new techniques, however, is still facing regulatory hurdles.

Figure 27: 3D printed house by Apis Cor and Contour Crafting process. Source: https://www.apis-cor.com/

Figure 26: Manufacturing of the 3D printed components by WinSun. Source: www.digitaltrends.com

Figure 28: 3D printed Canal House and detail of the concrete fill. Source: www.archiexpo.com

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Fused Deposition Modelling of plastic at large-scale was also explored for application in the building envelope. In February 2018, Melbourne-based Studio Roland Snooks designed and produced full scale 3D-printed wall panels for a meeting room at Monash University’s senseLab. This was done by using a three-metre arm robot, extruding polycarbonate (Figure 29).

To meet the ambitions of engineering and industries, large machines for FDM are being developed. Together with DUS Architects, the Dutch company Aectual operating in the field of industrial production technologies and software tools, developed XL-3D printers that can print massive products up to 1.6 x 1.6 x 4.5 meters in one go (Figure 30). The German company Bigrep produces large machines for FDM of large-scale objects. The Bigrep One features a build volume of x 1005 y 1005 z 1005 mm with 1mm-nozzle standard extruder.

Façade component scale

For the façade component to be designed, a panel with a standard width of 1.5 m, spanning from slab to slab (approximately 3 m) is being considered. For the production of a component as such different options are possible in terms of scale, assembly and site of production. The component could be manufactured on site or in a factory and then transported, as a single piece element or in different modules to be assembled.

As regards production on site, it should be assessed whether production in an uncontrolled environment is feasible, considering to the limitations of different techniques and materials. Particularly for extrusion-based techniques, heating and cooling temperature of the material should be controlled in order to avoid differential expansion and shrinkage, which lead to residual stress and warping in the material. The main advantage for production on site would be reducing cost and time of transportation. However, given the scale of the façade elements, this is not expected to have a considerably positive effect.

If fabrication off site is considered, production in one go or assembling of smaller modules can be considered. In order to fully exploit the possibilities offered by AM, production of a single element component would be optimal to cut off the assembly time and to challenge the current concept of façade component based on assembly of different elements. However, printing large-scale objects always comes with the risk of inaccuracies and flaws. Since differential cooling of adjacent material layers causes warping, the resulting deformation add up layer by layer and results in bigger defects in case of big objects. A similar trend occurs for residual stress.

The same concept of reducing assembly related issues could be valid even with production of different modules. This could be manufactured at the same time by different machines and in the same place, thus easing the assembly phase. For the scope of this research, the possibility of printing large-scale objects also depends on the availability of the technology which is more difficult to access to compared with standard desktop machines.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-site production</td>
<td>Reduced environmental impact, time and cost</td>
</tr>
<tr>
<td></td>
<td>Risks related to uncontrolled environment</td>
</tr>
<tr>
<td>Off-site production</td>
<td>Easy control over manufacturing process</td>
</tr>
<tr>
<td></td>
<td>Transportation is required</td>
</tr>
<tr>
<td>Single element</td>
<td>Fully automated process</td>
</tr>
<tr>
<td></td>
<td>Reduced labour intensity</td>
</tr>
<tr>
<td></td>
<td>Limited availability of large-scale machines and higher cost</td>
</tr>
<tr>
<td></td>
<td>Risk of larger inaccuracies and defects in the product</td>
</tr>
<tr>
<td>Multiple modules</td>
<td>Better control over quality of the product</td>
</tr>
<tr>
<td></td>
<td>More accessible and affordable technology</td>
</tr>
<tr>
<td></td>
<td>Labour intensity increased to some extent</td>
</tr>
</tbody>
</table>

Table 6: Expected pros and cons of small scale and large scale production

References:


2.3 RELATION BETWEEN GEOMETRY AND STRUCTURAL PERFORMANCE

In the field of structural design, the relation between performance and geometry has been widely investigated by formulating optimisation problems. Structures can be optimised to carry and sustain loads in the best way and to achieve certain performances, for example in terms of stiffness and strength. Structural optimisation can be performed at three different levels (Figure 31). Sizing optimisation consists in finding the optimal thickness and dimension for a given structural element. Shape optimisation has the form of the boundary as design variable, given a predefined boundary and connectivity of the elements. Topology optimisation is the most radical approach to structural optimisation and consists in finding the best material distribution for a set objective starting from a solid volume of material (Prayudh, 2016).

![Figure 31: Structural optimisation levels. Source: Gebisa & Lemu (2017)](image)

2.3.1 Topology Optimisation

Topology optimisation (TO) is a structural optimisation method that combines a numerical solution method (Finite Element Analysis) with an optimization algorithm that iteratively improves the material distribution within the design space, given a set of boundary conditions and loads.

Topology optimisation is meant to solve a continuum problem by discretisation of the design domain into finite elements, that are assigned a state value describing the required material density for the target structural performance (Panesara et al., 2018).

The mathematical definition of a structural optimisation problem consists of:

- **Design variable** \( x \): a parameter or a vector of parameters that describe the design and can change during the optimisation (geometry, material distribution);
- **Objective function** \( f \): a function that returns values describing the goodness of the design. This can be either maximised or minimised;
- **State variables** \( y \): a variable that represents the structural performance, depending on the design variable (stress, strain, displacement);
- **Design space** \( \Omega \): the desired volume for the design and the fixed parts of the geometry that cannot be modified during the optimisation;
The most common approach is the minimization of the objective function. For example, minimising the compliance of the structure leads to maximising its stiffness. A typical formulation for this problem is the following:

\[
\begin{align*}
\min_{\rho} & \quad f(x, y(x)) \\
\text{subject to} & \quad \text{design constraint on } x \\
& \quad \text{state constraint on } y(x) \\
& \quad \text{equilibrium constraint}
\end{align*}
\]

The equilibrium constraint is expressed by:

\[
F(x) = K(x) U \quad [18]
\]

where \(K(x)\) represents the global stiffness matrix and \(F(x)\) is the global load vector.

A state constraint function \(f(y)\) representing the state variables can be introduced, which can serve as constraint to the optimization task. It is usually formulated such that \(f(y) \leq 0\). The formulation above is called simultaneous formulation as the equilibrium of the structure is solved simultaneously with the optimisation problem. Often the state function depends on the geometrical variable \(x\). For example, the state function can be represented by the nodal displacement vector \(u(x)\), which is solved for:

\[
U(x) = K(x)^{-1} F(x) \quad [19]
\]

Such a formulation already takes into account the equilibrium constraint, so that the optimisation problem can be described with the so called nested formulation:

\[
\begin{align*}
\min_{\rho} & \quad f(x) \\
\text{subject to} & \quad g(u(x)) \leq 0
\end{align*}
\]

According to the nature of the geometrical variable \(x\), the problem can be either a size optimisation, when \(x\) is the thickness of the structural element, a shape optimisation where \(x\) is a value representing the boundary of the state function or a topology optimisation. In this case \(x\) represents the connectivity of the domain, describing features such as number and size of holes in the domain.

**Material Interpolation**

In mathematical terms, topology optimisation seeks an optimal subset \(\Omega\) belonging to \(\Omega\). Where \(\Omega\) is an allowable design domain. The design variable \(x\) is the density of the material \(\rho\), accounting for the elemental densities \(\rho_e\). In this formulation \(\rho_e=0\) describes a void element and \(\rho_e=1\) describes a filled element.

A material model is defined for which the stiffness \(E\) depends on the density and can be expressed by:

\[
E(\rho) = \rho \cdot E^0 \quad [20]
\]

Where \(E^0\) represents the Young's Modulus of the basic material to be distributed on the domain. This solution treats the density as a discrete variable. Therefore, a large number of finite elements is preferred to get attainable topological complexity, resulting in a high computational cost. For this reason, the integer problem described above can be formulated as a continuous function so that \(\rho\) can take values between 0 and 1 (Bends et al., 2014). The most common method used for this formulation is the SIMP (Solid Isotropic Material with Penalization). The density function in each point of the domain is expressed by:

\[
E = \rho^p \cdot E^0, \quad \rho \text{ belongs to } [\rho_{\text{min}}, 1], \quad p > 1 \quad [21]
\]

where \(p\) is the penalizing factor that corrects elements with intermediate densities to approach a value of either 0 or 1. This value is also introduced as a manufacturing constraint that accounts for the possibility of creating material with intermediate density.

**Minimising Compliance**

One of the most important structural aspects for the façade is dealing with deformations caused by the loads acting on it, namely dead load and horizontal wind loads. The most common objective function to maximise the global stiffness of a structure is to minimise its compliance. The compliance is defined as the equivalent strain energy, derived by the FE solution (Larsson, 2016). Minimised strain energy results in a high stiffness of the structure. The compliance is defined as:

\[
C(\rho) = f^T u \quad [22]
\]

where \(u\) is the global displacement, solving the equilibrium \(F = K(\rho) U\) is the summation of the elemental stiffness matrix in the domain. To prevent the optimized structure from ending up with the full design volume, a volume constraint is also imposed.

### 2.3.2 Topology and Additive Manufacturing

**TO in traditional design processes**

Compared to other structural optimisation methods, topology optimisation enables the exploration of a very large design space. The complexity of the topological designs resulted from optimisation is often a problem for the construction of CAD models and, most importantly, it is often difficult to guarantee that the optimised design will be manufacturable with traditional production techniques. A common practice in the engineering field is to interpret the organic result of the optimisation into simplified shape that correspond to standard structural elements. The constraints related to the manufacturing techniques, such as the need of tool access or mould removal can be included in the actual optimization by limiting the topology to feasible designs. All these comes at the cost of optimal structural performance and use of the material.

**AM as natural counterpart to TO**

Application of AM suggests new ways of producing complex geometries that are not feasible with the conventional processes (Calabrese et al., 2017). Due to the layer-wise manufacturing approach, geometrical complexity can be easily produced without significant effects on the cost. In relation to TO, this greater design freedom allows for a better approximation of the optimised shape. This natural synergy between the optimisation method and the manufacturing process also results in reduction (or even elimination) of material wastage.

**Opportunities**

As presented by Panesar et al. (2018), research has been carried out exploring the potential of TO in relation to additive manufacturing. Among the different approaches, the use of un-penalised SIMP method looks promising for its ability to better interpret the outcomes of the optimisation. As shown in the previous chapter, the SIMP method penalises intermediate material densities in favour of solid-void design that are most cost-effective in terms of manufacturing. This artificial penalisation means compromising on the optimality of the design in favour of a feasible and cheap production process. With its ability to build complex, mesostructured geometries, AM is the perfect manufacturing technique to build intermediate densities in the material.

This approach involves designing with cellular solids whose density can be changed inside the design domain. The properties of the cellular structures, such as porosity for open and closed cells and struts...
cross section for lattices, can be graded according to the density map derived by TO. The synergy between TO, AM and cellular solids also brings other advantages such as minimisation of the residual stresses in the structures due to the porosity of the material and fewer supports needed when self-supporting unit cells are designed.

**Challenges**

Although representing a promising approach for different reasons, the potential of AM complex geometries for interpreting the result of TO is still an ongoing area of research. As reported in Panesar et al. (2018), the majority of software that can be used for generating lattice structures, such as Grasshopper plug-in Intralattice, 3-Matic by Materialise and Within from Autodesk, lacks the ability to create graded cellular structures according to a 3D density map resulted from TO. The only exception is Optistruct from Altair which is able to integrate one simple type of lattice geometry into the optimisation process. An effective workflow for the interplay of the two methods is still to be defined.

Other challenges have been pointed out by Brackett et al. (2011) and regard the mesh resolution of the result geometry, the manufacturing constraints and the post-optimisation geometry handling. First of all, the complexity of the optimal geometry can be described within the limits of mesh representation. The finer the mesh, the more accurate the results and the more design variables need to be handled in the process. This could be prohibitive for the computational stage itself, especially when dealing with the design of big-scale components, as the façade panel considered in this study. While seeking the highest level of optimisation, whatever the computational cost, is still needed for certain applications such as in the aerospace structure, this study deals with exploring the possibility of geometrical complexity offered by AM specifically for applications in the Built Environment. This means that a synthesis between optimality of the design, manufacturability on large scale and costs (especially in terms of time), is a major issue to be addressed.

Secondly, AM still has some manufacturing constraints that need to be taken into account either within or after the optimisation process. These mainly regard dimensional accuracy, build angle, need of support material and wall size. As regards topology, the need of support materials and minimum wall size are the most relevant parameters. An approach to limit this issues is to modify the design to make it self-supporting. Depending on the application it can be decided whether it is more effective to redesign the structure, making it heavier, or to manually remove the support structure after the printing. Given the scale of a façade component, the possibility of designing a self-supporting component straight for the printer is the desired result that would lead to significant saves in time and labour intensity of production. Yet, research on methods to incorporate AM constraints into the TO process is scarce. Optistruct by Altair is among the few software options that embed a minimum number thickness constraint. The use of small values for thickness of members would lead to minimum overhanging spans in the geometry and therefore minimum need for supports. Finding the right value for such minimum, however, remains matter of trial and error. To this purpose, general considerations regarding maximum free span between components and acceptable angles to be manufactured can be made and a method to incorporate guidelines into the optimisation process should be elaborated.

Another important aspect to take into account is the handling of the geometrical complexity resulted from the optimisation. The result geometry form TO usually needs an intermediate step of simplification and smoothing before it can be transformed in a STL file for the machine. This step is usually done manually, in a CAD environment. This operation may be very difficult and time-consuming depending on the specific design conditions. Some software tools are available specifically for handling STL files directly generated from the optimisation process and apply smoothing and re-meshing operations, by-passing the cumbersome step of translating the geometry in a CAD environment. The effectiveness of such techniques will be evaluated according to the specific design geometry.

### 2.3.3 Case Studies

**Spider Bracket by Materialise, Renishaw & Altair**


The design is a result of a topology optimisation process and consists of light-weight strong hybrid lattice structure. The lattice structure is also beneficial for the thermal properties of Titanium. For the topology optimisation Altair’s Optistruct was used which has two options for the optimisation method: Level set and SIMP. Moreover, the software enables the integration of the manufacturing constraints to the optimisation process.

In the resulting geometry, the irregular interface between the lattice and the solid mesh, which can lead to difficulties in manufacturing and to stress accumulations, was reconstructed and smoothened using Materialise 3-matic software. This tools also allowed for the optimisation of the design in order to minimise the need of support geometries. Materialise Magic software was used to find the optimal build orientation, position the part within the build envelope and generate the support structures. Renishaw Build Processor was used to slice the geometry and prepare the file for the SLS machine.

This project proved that topology optimisation with solid and lattice structures results in geometries which can be manufactured through AM. This was possible through the close collaboration of three companies with their specific expertise in structural optimisation, data handling and additive manufacturing.

---

The project entails the topology optimisation of a structural node for a tensegrity structure. A tensegrity structure is based on the structural principle of using isolated compression members in a net of continuous tension. The nodes connecting the struts within the structure have slightly different shapes due to the need of accommodating the attached cables at different angles and positions. An additional challenge to the design is integrating a lighting fixture in the structural node.

An overall weight reduction of 75% compared to the initial standard design was achieved in the topologically optimised element. Altair's OptiStruct was selected as the program for the topology optimization of the node design. The design space was modelled in a Rhino/Grasshopper environment where the design space and boundary conditions could be set up parametrically to enable different cable configuration for another node. CAE software from 3D Systems was used to improve the design from the production perspective. The production through AM consisted in the printing of sand moulds using binder jetting technique.

Overall the design was approached in an innovative way by making use of the potentials of AM and computational design. However, the objective to automate the generative process for all nodes was not achieved. The selected software showed good performance suitable for a specific task but lacked desired interaction and ease of operability for the design process.


2.3.4 Tools for Topology Optimisation

For the feasibility of this study, the choice of software tools will play a very important role. In the design exploration phase the most suitable tool for the design purpose will be identified, aiming for a reasonable balance between cost of computational process and optimal design and for a certain degree of flexibility. Table 7 summarizes the characteristics of the most common software tools for topology optimisation.

Table 7: Evaluation of different software tools for topology optimisation

<table>
<thead>
<tr>
<th>Software</th>
<th>Developer</th>
<th>Flexibility</th>
<th>TO Method</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>BESO3D</td>
<td>RMIT</td>
<td>Possible integration with Rhinoceros and Pythonscript</td>
<td>BESO method</td>
<td>High level of flexibility</td>
</tr>
<tr>
<td>Altair OptiStruct</td>
<td>Altair (commercial license required)</td>
<td>Stand-alone software</td>
<td>Level Set/ SIMP</td>
<td>Possibility of including manufacturing constraints</td>
</tr>
<tr>
<td>SolidThinking Inspire</td>
<td>Altair (commercial license required)</td>
<td>Stand-alone software</td>
<td>Level Set/ SIMP</td>
<td>Simple user interface Possibility of including manufacturing constraints</td>
</tr>
<tr>
<td>Millipede</td>
<td>Panagiotis Michalatos</td>
<td>Plug-in for Grasshopper Parametric Environment</td>
<td>SIMP</td>
<td>2D and 3D topology optimisation Straight-forward visualisation Iso-surface utility</td>
</tr>
<tr>
<td>tOpos</td>
<td>Archiseb</td>
<td>Plug-in for Grasshopper Parametric Environment</td>
<td>SIMP</td>
<td>100X faster than competitive TO plug-ins</td>
</tr>
</tbody>
</table>

References:


2.4 RELATION BETWEEN GEOMETRY AND THERMAL PERFORMANCE

The relation between geometry at meso-structure and thermal performance has been widely investigated for the development of insulation materials. Lately, legislation has acted as a catalyst for the latest advancements in the field and new high performance insulating materials have been developed, by manipulating cell structure, infill material or creating vacuum for the cavities. Common insulating materials in the market are characterised by either an open or closed cell structure. It should be pointed out that such structures have a certain degree of randomness as foaming manufacturing technique does not enable full control over the geometry. For the scope of this study, ordered and regular geometries will be designed resulting in more predictable thermal properties.

Open Cell Structure

Mineral wool products have open cell structures. EPS insulating materials, which are technically closed cell structure, behave like open cell materials due to the linking across the structure of the air pockets. A typical open cell structure is presented in the Figure 34. In the manufacturing process, the air pockets created by forcing air into the fibres are locked into position by the activation of a binding agent. The blowing agent forms irregular pockets that are linked together into a continuous interconnected capillary network. Open cell insulation has a permeable structure to moisture and vapour. The thermal insulation property is given by the ability of the structure to hinder the path of the heat transfer. Small air molecule collisions move the heat from warmer to cooler fibres.

Closed Cell Structure

Insulation materials such as XPS have a closed cell structure which is created by controlled introduction of blowing agents in the manufacturing process. These form a dense matrix of individual cells that are formed as bubbles of gas with low thermal conductivity. As can be seen in Figure 35, the cell walls are extremely thin thus greatly reducing conduction and gas movement is confined within the cell boundaries. Limited heat transfer occurs between the cells and no water vapour can contaminate the cells. Overall, thermal performance of closed cell structure is better, with lower conductivities.
2.4.1 Case Studies

The Spongy Skin: Master Thesis by Valentini Sarakinioti

The spongy skin is a concept for a façade panel produced by additive manufacturing where the potentials of cellular structures for thermal insulation are explored. At first, the potentials of cells with spherical shape of 1mm diameter were investigated. While the thermal conductivity resulted to be satisfying, in the range of 0.05 W/mK the slicing process for the geometry was time consuming and with high risk of errors. The final design consists of Waire-Phelan structures, with polyhedra of 1 cm and 5 cm size. The underlying principle for achieving structural stiffness is that of the sandwich panel with a porous core between two stiff plates. The core is made up of large polyhedra (5 cm size and wall thickness of 1.5 mm) which are connected to create tubes. The tubes are filled with aerogel to increase the thermal resistance. Moving towards the external part of the panel smaller polyhedra are used to provide stiffness.

Overall, the study proves that thermal conductivities in the range of 0.05-0.07 W/mK can be achieved and up to 0.028 W/mK in case of large polyhedra with 1 mm thickness walls and aerogel infill. Cellular structures are capable of reaching interesting results in terms of thermal performance but the minimum achievable thickness of the walls is an issue. Moreover, manufacturing feasibility is an issue as polyhedral structures require a non-uniform path of the nozzle to be printed, resulting higher printing times.


SPONG3D: Research Project by 4.TU Federation

The project demonstrates that 3D printing enables production of mono-material components integrating multiple functions for optimised thermal performance. Moving from the results of the Spongy Skin project, this research further investigated the relation between cellular structures, thermal insulation and 3D printing. In this case polyhedral cells are put aside due to the high printing time required, and elongated cells are used with higher porosity and reduced printing time. The cells are elongated up to 15 cm in two directions and a dimension of 10-20 mm is kept in the direction of the heat transfer to minimise convection. Wall thickness is in the range of 1 mm. Printing time is reduced to less than half compared to printing samples of polyhedral structure with similar size. The achieved thermal conductivity of the samples ranges between 0.09 and 0.1 W/mK. The study suggests directions for further research: improving the thermal conductivity, developing a systematic process to design the insulation part reducing material and easing the production and investigating on the thermal properties of printing materials.

2.4.2 Tools

As discussed in section 2.1.4, Analytical models are straightforward and easy to integrate within the design process. However, Sarakinioti (2016) shows how the theoretical behaviour of the specimens is not exactly confirmed by the physical tests, due to the simplifications involved in both processes.

Software tools are available that can provide more reliable results by studying the heat transfer problem through numerical methods. Among these, COMSOL Multiphysics is a cross-platform finite element analysis, solver and multiphysics simulation software which stands out for its flexibility. This tool allows the coupling of different physics to observe multiple effects in the same context and accepts various user-defined inputs, giving the freedom to predict any desired situation (Farrugia, 2018). Moreover, any geometry can be imported in the software as 3D mode. With this flexibility also comes a certain degree of complexity. Therefore, using the software may require some time to familiarise with the interface and the system. TRISCO is commonly used for building engineering designs. This is a thermal analysis program for steady state heat transfer in three-dimensional rectangular objects consisting of different materials and submitted to different boundary conditions. The software requires the user to model the geometry as rectangular blocks with vertices lying on grid points. For an input of geometry and thermal properties, a system of linear equations is calculated based on the energy balance technique, and solved using a fast iterative method.

To the extent of our knowledge, there is no available tool that can be integrated in the parametric environment of Rhino/Grasshopper to assess the heat transfer of cellular and lattice structures. Simple analytical calculations could be integrated in the parametric model for the thermal performance assessment, provided that the results are reliable enough to drive the design process.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMSOL Multiphysics</td>
<td>Possibility of importing 3D models with complex geometries</td>
</tr>
<tr>
<td></td>
<td>Multiple user-defined inputs are accepted</td>
</tr>
<tr>
<td></td>
<td>Possibility of coupling multiple physical effects to simulate realistic scenarios</td>
</tr>
<tr>
<td>TRISCO</td>
<td>Simple interface</td>
</tr>
<tr>
<td></td>
<td>Limited to standard heat transfer problems</td>
</tr>
<tr>
<td></td>
<td>Geometry has to be simplified and rebuilt within the software</td>
</tr>
</tbody>
</table>

Another way to assess the thermal performance is physical testing. Simple tests could be done to study the heat transfer through a material sample and derive the thermal resistance value of the component by measuring the heat flux and the temperatures at the inner and outer surface of the sample (Figure 38). For such measurements, it is necessary to have create an environment with a temperature difference; this could be done by using a heat source such as a light bulb or a refrigerator. Then, a thermocouple and a heat flux plate are needed, to be placed on the surface of the sample. The thermocouple and heat flux plate require a data-logger to transfer the information to a computer. The data can be read in the computer using a dedicated software and the thermal resistance (and thus the conductivity) can be calculated knowing the heat flux and the temperature difference (Sarakinioti, 2016).

The most reliable method to measure the heat flux is based on the guarded hot plate. This method requires a heating plate sandwiched in between two samples of the material being measured. An unheated “cold plate” is then placed on either side of the insulating material. As soon as the system has reached thermal equilibrium, the thermal conductivity is calculated from the temperature rise of the cold plate, which represents the heat conduction through the insulating material. Since this physical testing requires the production of samples, the testing of the production technique is part of the process. This is useful to the final objecting of producing a full scale prototype but is not able to provide guidelines to be easily and quickly integrated in the design process.

![Figure 38 : Heat flux testing method](image1)

![Figure 39 : Scheme of guarded hot plate testing method](image2)

**References:**


3D Finite Element Analysis. Retrieved from https://www.feaservices.co.uk/thermal-analysis/3d-finite-element-analysis

CHAPTER 03 - DESIGN BOUNDARIES

This chapter presents the boundaries that were set for the design of the façade element according to information retrieved in the Foundation Knowledge Phase. The target for the design in terms of performance are set along with the design space. The feasibility of production through additive manufacturing is discussed in terms of most suitable technique and material. Additionally, guidelines for the geometrical exploration are stated and a digital-physical workflow is proposed for research-through-design and performance-driven design.
3.1 Component

According to the outcomes of the literature research, the boundaries for the study were defined in terms of design principles, production process and target performances. The envelope component considered for this study is a modular façade panel. Although additive manufacturing enables production of semi-transparent or translucent items, this component serves as opaque envelope element for which visual comfort requirements are not taken into account. The component was designed parametrically to maximise design freedom: in principle a number of different solutions could be generated depending of the specific boundary conditions of the façade element such as elevation and orientation. Taking advantage of the capability of additive manufacturing to produce mass customised products, each façade element could be specifically designed as a unique piece according to local requirements (Figure 40).

3.2 Performance

In terms of performance integration of structural stiffness and thermal insulation was considered as the objective of the design. The aim is achieving the same performance levels currently required from building envelope elements. In particular, the following condition should be met:

- **Rc value of 4.5 m2K/W or more.** The aim is to at least comply with the Dutch Bouwbesluit and reach the highest possible thermal resistance, in the perspective of the BENG requirements which will have to be met by buildings in 2020.

- **Verification of maximum deflection** in accordance with standard EN 13830, considering the vertical dead load of the façade panel, the horizontal wind load acting on the façade panel.

3.3 Material

Polymers are the most promising materials for the purpose of this study due to their thermal properties. For the specific application, a polymer with good mechanical properties needs to be chosen. Optimatter is a web platform that provides a wide range of data on materials, technologies and parameters and calculates the best printing configuration based on the user’s requirements. According to its database, a classification was made on the different polymers available for Fused Deposition Modelling. The polymers were assessed according to:

- **Ease of printing:** how easy it is to print a material in relation to bed adhesion, maximum printing speed, frequency of failed prints, flow accuracy, ease to feed into the printer;
- **Visual quality:** how good the finished object looks.
- **Maximum stress:** maximum stress the object can undergo before breaking when slowly pulling on it;
- **Elongation at break:** maximum length the object has been stretched before breaking;
- **Impact resistance:** energy needed to break an object with a sudden impact;
- **Layer adhesion:** how good the adhesion between layers of material is and how uniform the material is;
- **Heat resistance:** maximum temperature the object can sustain before softening and deforming.

The main pure polymers that exist in the market today were ranked considering the above criteria, as shown in Figure 41. These are PLA, ABS, PET, Nylon, TPU (Flexible) and PC. All criteria are relevant for application on the building envelope and there is no obvious way to identify the best material of the list. PET stands out as a good alternative for the ease of printing and the average thermal and structural properties. PC appears to be an interesting option for its outstanding thermal resistance and strength. Additionally, PC looks promising from the perspective of fire resistance. A 3D-printed façade component made of PC could obtain a fire rating in the context of SenseLab project by Roger Snooks. A disadvantage of this material is that it requires specific adjustments when being printed such has high temperatures of nozzle and bed. Overall, PETG was considered the best alternative in terms of performance and ease of printing. Its lower cost makes it more appealing for application in the built environment.

![Figure 41: Research results on the properties of polymers for FDM. Source: https://www.3dhubs.com/knowledge-base/fdm-3d-printing-materials-compared](https://www.3dhubs.com/knowledge-base/fdm-3d-printing-materials-compared)
3.4 Production

In accordance with the material choice, the chosen production process is Fused Deposition Modelling. This technique is chosen for the simplicity of the process and the relatively low cost, which makes it appealing in the perspective of large-scale production for buildings. Moreover, the AE&T Department at the TU Delft Faculty of Architecture and the Built Environment has three FDM 3D printers available. Since the objective of the study is to test the feasibility of a 3D printed façade panel by producing a 1:1 prototype, a large build volume machine is required. The largest printer available at the Faculty is the Leapfrog Xcel 3D printer with maximum print dimensions of 550 x 500 x 2320 and a 1.2 diameter nozzle.

As discussed in Section 2.2.6, the façade component would be produced in one piece to minimise assembly and reduce labour intensity. A panel with a standard width of 1 m, spanning from slab to slab (approximately 3 m) is being considered. However, with the available technologies (printer and material), the production process may result in very large printing times and be prone to inaccuracies and defects. The façade panel prototype could then be produced in a small number of pieces. In this way, the production process can be controlled more easily and the prototype would still be able to showcase the concept. To this purpose, a connection between the different parts will have to be designed.

3.5 Geometries

From the literature research, some guidelines can be derived about the geometries to explore in this study, thus further defining the design boundaries. As regards the relation between structural performance and geometry, it has been shown that:

- Lattice structures are more efficient than cellular structures as their behaviour is prevalently stretch-dominated;
- Among different lattice structures, only triangulated ones are purely stretch-dominated;
- Symmetrical structures are preferred as they do not have a weaker or stronger direction and their orientation does not have to depend on the load case;
- Porosity influences Young’s modulus and strength of the structures so that the right balance must be found between structural performance, weight of the structure and printing time;

As regards the relation between thermal performance and geometry, it has been shown that:

- Closed-cell structures are the most efficient thermal insulators due to the presence of enclosed still air cavities;
- Shell structures may require printing infill or support geometries, increasing printing time;
- Polyhedral minimal surfaces such as the Weaire-Phelan are very efficient but can result in huge printing times as the path of the extruding nozzle is not continuous and problems in handling the geometrical data;
- Cell dimensions need to be designed in such a way that convection in the direction of heat transfer is minimised. One direction must be kept around 10-20 mm while the other dimensions can be larger;
- An alternative strategy is designing lightweight lattice/open-cell structures in such a way that the path of heat transfer is hindered and not continuous to minimise convection.
3.6 Design Environment

The design of the façade element will have two main focuses: the relation between performance and geometry and the integration of the structural and thermal performance. Such objectives require the design process to be flexible and to set itself in a parametric environment in which different design alternatives can be described and assessed. The easiest way would be having one single parametric model in which the geometries can be modelled and assessed.

As shown in section 2.2.3, there are possibilities for performing the topology optimisation and structural analysis within the parametric environment of Rhino/Grasshopper using different plug-ins such as tOpos and Millipede. Moreover, there are plug-ins that are useful to model cellular and lattice structures such as Crystallon. For the thermal performance the task is a more complex one as there are no plug-ins for Grasshopper which can be used for the thermal analysis of complex geometries and the software tools described in 2.3.4 require the geometry to be exported and then analysed in another digital environment. Physical tests can also be used but require the intermediate step of producing 3D-printed samples. Simplified analytical models can be used to study the problem and retrieve the thermal conductivity of a cellular geometry, as shown in section 2.1.4. These formulas could be integrated within the parametric model. However, the validity of these calculation methods must be verified in advance. This could be done by comparing the results with those from the numerical analysis and the experiments.

The design environment for this study is integrated in a digital-physical workflow (Figure 43).

![Digital-physical workflow for the study. Final configuration of the parametric environment](image)

Figure 43: Digital-physical workflow for the study. Final configuration of the parametric environment

References:


The 3D Printing optimization tool focused on materials. Retrieved from https://www.optimatter.com/
CHAPTER 03 - RESEARCH THROUGH DESIGN EXPLORATION

This chapter presents the results of the Research through design exploration phase, where the relation between geometry, thermal and structural performance was investigated in order to gain insight on the behaviour of cellular structures and retrieve guidelines for the design of the façade component. This phase entailed a comparative study of different cell topologies which were assessed according to their performance and their manufacturability through additive manufacturing. First, the different strategies adopted are discussed. Then, the outcomes of geometrical exploration, structural and heat transfer analysis are presented. Analytical models retrieved from the literature were used, along with software simulations and physical testing. The most relevant settings used for the software simulations are discussed, while further details about the digital methodology can be found in Chapter 5, where the digital workflow developed for this study is presented.
4.1 Strategy

Prior to starting with the design exploration, a workflow was defined within the design environment described in Section 3. In particular, the following guidelines are established:

- Geometry optimisation on the façade component is first developed at two different levels: the façade panel and the material meso-scale. The results are superposed in the Component Design phase.

  The relations between performance and geometries at meso-scale are first explored separately in order to gain insight on the specific design variables and parameters involved. In this way, it is possible to evaluate whether the same geometry can be used to serve both performances or it is best to define different functional areas within the façade panel to be designed with specific geometries.

The research through design phase aimed at retrieving useful data for the final component design, by answering the research questions. An overview of the workflow for this phase is shown in Figure 38, where each step in the research is highlighted along with its results and relation to the next phases of the design.

Figure 44: Optimisation workflow for design

Figure 45: Geometry exploration workflow

Figure 46: Overview of work-flow for research and design phase
4.2 Topology Optimisation of the façade component

At macro-level, geometrical optimisation consists in finding the optimal material distribution within the façade panel. This was done by performing topology optimisation, considering the design boundaries defined in Section 3. The target design is a 3 x 1.5 m panel which spans from slab to slab and is subjected to its own dead load and to a wind load of 1 KN/m² (Figure 47).

Details about the optimisation process, including tools used and settings are presented in Section 5.1.

Different options for support conditions were explored in order to retrieve material distribution alternatives. In particular, three options were considered:

- The panel is supported by four point-supports at the corners, which transfer the loads to the building slabs. The supports are restrain translations along x, y and z axis;
- The panel has a curtainwall-like support: it supported at the top by two point supports attached to the slab and rests on the panel below at the bottom. The point support restrain translations along x, y and z, while the line support restrains translation along z axis;
- The panel is supported by two line supports at the top and the bottom, transferring the loads to the building slabs. Both supports restrain translation along x, y and z axis.

The results of the optimisation are shown in Figure 45 in form of isosurfaces, to show which parts undergo the highest stress and, therefore, are required to have a higher density. Since the optimisation is performed using a SIMP method without penalisation, no element in the panel is assigned zero density but a range of prescribed density is generated. As material properties are not considered in the optimisation process, the results only indicate the overall structural behaviour of the structure. A proper structural analysis of the final geometry should be performed to retrieve results on stress and displacement of the structure. Therefore, the output of the optimisation is a list of the density values assigned to each finite element, indicating the percentage of material needed for the given boundary conditions.

As shown in Figure 48, in all three options higher material density is required in proximity to the supports, where the highest stress states are found. Moreover, due to the out-of-plane wind load, the panels deform inward, with highest deflections corresponding to the middle of the panel.

The different topological results were then assessed according to performance indicators such as relative density and potential for integration of the thermal performance as well as other possible façade components. In this way, the best alternative for the specific design requirements was evaluated. The assessment is presented in Section 5.1.
4.3 Lattice and shell geometry generation

Geometry exploration at meso-scale involved creating a parametric model to generate different cell geometries and retrieve information for performing analytical calculations on the thermal and structural performance. According to the information retrieved from the literature study relatively to thermal and structural properties of cellular structure, a pre-selection of geometries was made by considering the outcomes of the literature research relatively to the thermal and structural properties of cellular structures (Figure 49). In particular, for lattice geometries:

- Triangulated geometries were selected, as they enable a perfect stretch-dominated structural behaviour;
- Geometries with potential for hindering the path of heat transfer were chosen.

For shell structures, geometry types were selected according to two parameters:

- Ability to be self-supporting and to provide stiffness in the three directions;
- High volume-to-surface ratio to maximise porosity of the geometry and therefore increase the thermal performance.

The different cell geometries were generated parametrically, as presented in section 4.4. The generation process requires the definition of a unit cell and cell array into which the cell topologies are morphed to create a cellular solid (Figure 50). A suitable cell size was to be defined, using the findings of the literature research. To minimise the effect of convective heat flow within the geometry an elongated cell type was chosen, with a dimension of 2 cm along the heat transfer direction and 10 cm along the other two directions (Figure 51). In this way, heat transfer through the cells would be mainly caused by radiation between the cell surfaces and conduction through the solid and gas.

Given the influence of porosity on both thermal and structural performance, the different topologies were modelled to have a comparable density. Moreover, considering the manufacturing constraint of FDM, shell geometries were modelled with a thickness of 2 mm, while lattice structures were modelled with a 2 mm strut radius. The different geometries were then assessed and compared according to their thermal and structural performance, using analytical models, physical testing and software simulations.
4.4 Analytical models for thermal and structural performance

As presented in section 2.1.3 and 2.1.4, analytical models have been developed to calculate effective thermal conductivity, yield strength and Young’s modulus of cellular and lattice structures. These expressions are mainly dependent on the density of the geometry and cannot accurately take into account the effect of topology. However, they were useful to retrieve preliminary results and make a first comparison between the different options.

In this phase, the printing filament material was chosen, according to the process which was then used for producing geometry samples. In terms of thermal performance, common plastic filaments used in FDM have a comparable thermal conductivity ranging from 0.18 to 0.22 W/mK. On the contrary, the range of structural properties for plastic filaments is much wider, therefore the structural performance can considerably vary according to the chosen material. As the results of the hand calculations were compared with those of the physical testing on 3D printed samples, the material properties of the PET printing filament were used, which are presented in Table 9.

Using these as input values, the properties of the geometry alternatives were calculated using the models presented in the literature research. Particularly for the thermal performance, different calculation methods were used and compared. In general, the results proved to be quite consistent, with differences of ±0.005 W/mK in terms of effective thermal conductivity (Table 10). The results of the calculations in Table 11 show that geometries that perform the best in terms of thermal insulation perform the worse in terms of structure and vice-versa. This is because thermal conductivity increases with relative density and so do strength and modulus. For thermal conductivity a nearly linear relationship with relative density can be observed (Figure 51).

For this reason, it seemed interesting to compare these results with those of simulations and physical tests. In this, it was possible to assess how geometry influences the two performances and if there are possibilities for a geometry with a good behaviour on both thermal and structural performance.

![Analytical model's results and comparison of structural and thermal performance](image)

### Table 9: Material properties of printing filament

<table>
<thead>
<tr>
<th>Material</th>
<th>PET (InnoFil3D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>1340 kg/m³</td>
</tr>
<tr>
<td>$E$</td>
<td>2140 MPa</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>0.19 W/mK</td>
</tr>
</tbody>
</table>

### Table 10: Results from the analytical models- thermal conductivity of Gyroid Shell

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice</td>
<td>0.22</td>
<td>0.034</td>
<td>43</td>
<td>0.5</td>
</tr>
<tr>
<td>BC (int)</td>
<td>0.18</td>
<td>0.037</td>
<td>107</td>
<td>1.2</td>
</tr>
<tr>
<td>BC cubic</td>
<td>0.23</td>
<td>0.047</td>
<td>164</td>
<td>1.8</td>
</tr>
<tr>
<td>PC cubic</td>
<td>0.17</td>
<td>0.031</td>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>Vertex Octa</td>
<td>0.14</td>
<td>0.035</td>
<td>100</td>
<td>1.1</td>
</tr>
<tr>
<td>Star Tetrahedron</td>
<td>0.17</td>
<td>0.039</td>
<td>121</td>
<td>1.3</td>
</tr>
<tr>
<td>Tetrahedral</td>
<td>0.17</td>
<td>0.039</td>
<td>121</td>
<td>1.3</td>
</tr>
<tr>
<td>Gyroid</td>
<td>2</td>
<td>0.043</td>
<td>27</td>
<td>1.9</td>
</tr>
<tr>
<td>Diamond</td>
<td>2</td>
<td>0.052</td>
<td>156</td>
<td>3.2</td>
</tr>
<tr>
<td>Schwartz P</td>
<td>2</td>
<td>0.049</td>
<td>134</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Table 11: Analytical model’s results and comparison of structural and thermal performance

![Relation between porosity and effective thermal conductivity according to the analytical model results](image)

![Relation between porosity and Young’s Modulus according to the analytical model results](image)
4.5 Production with Additive Manufacturing

In order to verify the results of the analytical calculations, geometry samples were produced using FDM technique. This was also useful to gain insight on the production technique and on the use of the 3D printers. For the production, a LeapFrog desktop printer was made available at the TU’s Lama laboratory at the TU Delft Faculty of Architecture and Built Environment. The size of the samples was defined according to the machine build volume and to the set-up of the heat flux physical test. A sample of 25 x 17 cm was modelled in Rhino-Grasshopper, corresponding to a 3 x 2 cell array. The cell size is 8,3 x 8,5 x 1,7 cm, with the smallest dimension in the direction of the heat transfer.

As explained in section 2.2.1, the geometry modelled in Rhino-Grasshopper had to be exported as a solid or a closed mesh in STL format to be then transferred to the slicing software. Simplify3D was used as slicing software, which was installed on a dedicated computer for the 3D printer. In this phase careful attention was taken to properly define the mesh to be exported. This was particularly relevant for the strut joints in lattice cells and for the mesh of cellular geometries to give a proper thickness to the geometry.

The initial plan involved modelling and producing two samples for each geometry, one with a single-cell thickness and one with a three-cells thickness, in order to compare the thermal behaviour. However, the production of the single-layer samples resulted to be considerably time-consuming, with up to four hours printing time. In the end three different geometries were printed in the single layer configuration: Schwartz’s P, Gyroid and Diamond.

The slicing software was connected to the 3D printer and data regarding nozzle size and extrusion were inserted. In particular, a nozzle with size of 0,95 mm was used, which corresponds to about 1,2 mm in the printed sample. The main settings regard:

- Temperature of the extruder and the heated bed: 210°C, according to material specifications;
- Extrusion speed: 30mm/s;
- Cooling settings: 40% power).

During the sample production the relation between different settings and printing quality was explored. In general, accuracy and quality of the printed products was found to be very dependent on the temperature settings and the speed of the extrusion. Low speed printing resulted in much more accurate prints and the extruder temperature determined the presence of air bubbles within the extruded filament. By tweaking the settings, the quality of the prints could significantly improve as can be seen in Figure 55, picturing the last sample printed.

The production of lattice structures proved to be much more challenging. The difficulty in printing such geometries is due to the horizontal slicing which results in overhanging geometries that need a support structure to be properly printed. Different alternatives were considered to produce the samples with the most efficient build orientation but in the end no one was successful (Figure 54). Generally speaking, horizontal slicing and traditional FDM technique are not the most suitable techniques to produce lattice geometries.

Power bed fusion techniques would allow production of lattices geometries without need for support materials, but as already pointed out in Section 2.2, these techniques are generally more expensive and unsuitable for large scale geometries. Lattices can also be produced using a robotic arm coupled with an extruder. The production of the lattice does not proceed by horizontal-layer extrusion but by multi-plane extrusion so that each beam of the lattice is extruded in one. This process requires a very effective cooling fan so that, once extruded, the struts retain their position and do not collapse.

Since it was not possible to perform physical testing on these geometries, further evaluation of lattice structures had to be carried out by means of software simulations.
4.5 Physical Testing

Simple physical tests were carried out to retrieve the effective thermal conductivity of the printed samples. To this purpose, the testing set-up available in the laboratory 08.01 West130 at the Faculty of Architecture and Built Environment was used.

Test setup

This consists of a box of polystyrene which designates an enclosed space in which the climate conditions can be changed to create a temperature difference with the room. The box can be heated up in the inside by a light bulb, equipped with a aluminium sheet shell to enhance the heat transfer to the box and make sure no direct radiation reaches the sensors. Moreover, the box has a hole on one of the side in which the material sample to be tested can be placed, as shown in Figure 59. The samples were prepared for the experiments by covering the exterior surfaces with a 1 mm transparent VIVAK sheet (Figure 58). This material was chosen because, being a type of PETG, it has comparable thermal properties to the printing filament used for the samples.

According to Fourier’s Law:

\[ q = \frac{\Delta T}{R_{tot}} \text{ [W/m}^2\text{]} \]  \[ 23 \]

Therefore, in order to calculate the thermal resistance of the sample, heat flux and temperature difference should be known. Temperature was measured using thermocouples at 4 different places: inside the box, at the inner side of the sample, at the outer side of the sample and outside the box (Figure 56). The sensors were connected to a data logging systems (Eltek Squirrel 1000 series), transferring the data to the Darca Software for full operational control of the Squirrel. Heat flux was measured using heat flux sensors (HF01 from Hukseflux) which were placed at the two sides of the sample to record the heat flowing in and out of it.

\[ q = \Delta T/R_{tot} \text{ [W/m}^2\text{]} \]  \[ 24 \]

Figure 60 shows the positions of the sensor for the two measurements rounds on the Gyroid sample. Temperatures and heat flux data were exported and the heat flux values were converted from Volts to Watts, considering the sensitivity of the sensors. The thermal resistance was then calculated as:

\[ R_{tot} = \frac{\Delta T}{q} \]  \[ 24 \]

where \( \Delta T \) is temperature difference between the surface temperature of the inner side of the sample and that of the outer side of the sample. Then, the effective thermal conductivity of the sample of thickness \( d \) was calculated as:

\[ \lambda_{eff} = \frac{d}{R_{tot}} \]  \[ 25 \]

Results

Table 12 presents the results of the measurement and the calculation, according to the data exported from the Darca software (Appendix C). The final effective thermal conductivity is the average between the results from the two measurements from each sample.

It can be observed that the heat fluxes entering and leaving the samples are never exactly equal, even if the slight difference between the sensitivities of each sensor is considered. This can be explained by the way measurements were taken: even if the heat flux sensor were placed around the same location at the internal and external side of the sample, the exact position could not be identified. More consistent results could have been retrieved if the average heat flux entering and leaving the entire external surfaces of the sample was considered.

The three geometries have a similar thermal conductivity in the range of 0.07 W/mK, which corresponds to a decrease of 65% compared to the thermal conductivity of the solid material (\( \lambda = 0.19 \text{ W/mK} \)). The best geometry is the Diamond whose thermal conductivity is 0.063 W/mK. This means that in order to achieve an RC value of 4.5 mK/W the façade panel should have a thickness of about 28 cm.

Contrary to what could be expected, the effective conductivity of the geometry is found to be lower when the sensor was placed on the solid part. This may be due to the inaccuracies of the testing process, which can result both from the tools (heat sensor, thermocouple) and from the way the measurements were done. To gain insight on these aspects, the results of the test were compared to those of software simulations.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Thickness [m]</th>
<th>( T_{in} ) [°C]</th>
<th>( T_{out} ) [°C]</th>
<th>( q_{in} ) [W/m²]</th>
<th>( q_{out} ) [W/m²]</th>
<th>( R_{tot} ) [°C/W]</th>
<th>( \lambda_{eff} ) [W/mK]</th>
<th>( \lambda_{AV} ) [W/mK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond_1</td>
<td>0.019</td>
<td>48.8</td>
<td>46.4</td>
<td>26.1</td>
<td>23.7</td>
<td>63.0</td>
<td>46.7</td>
<td>0.024</td>
</tr>
<tr>
<td>Diamond_2</td>
<td>0.019</td>
<td>48.2</td>
<td>46.3</td>
<td>28.3</td>
<td>22.3</td>
<td>73.6</td>
<td>67.0</td>
<td>0.026</td>
</tr>
<tr>
<td>Gyroid_1</td>
<td>0.019</td>
<td>48.6</td>
<td>46.7</td>
<td>28.8</td>
<td>22.3</td>
<td>58.5</td>
<td>62.7</td>
<td>0.025</td>
</tr>
<tr>
<td>Gyroid_2</td>
<td>0.019</td>
<td>49.1</td>
<td>46.7</td>
<td>28.2</td>
<td>22.1</td>
<td>89.7</td>
<td>61.4</td>
<td>0.024</td>
</tr>
<tr>
<td>Schwartz_P_1</td>
<td>0.019</td>
<td>48.6</td>
<td>47.8</td>
<td>27.7</td>
<td>22.9</td>
<td>63.3</td>
<td>66.0</td>
<td>0.311</td>
</tr>
<tr>
<td>Schwartz_P_2</td>
<td>0.019</td>
<td>49</td>
<td>50.8</td>
<td>28.9</td>
<td>22.5</td>
<td>93.5</td>
<td>84.0</td>
<td>0.247</td>
</tr>
</tbody>
</table>

Table 12 : Resulting thermal conductivity from physical tests
4.6 Simulation in COMSOL Multiphysics

Simulations were performed to gain insight on the thermal behaviour of the different geometries, with three main objectives:

- Compare and verify the results from the physical tests;
- Define a reliable model to test the thermal conductivity of different geometries;
- Retrieve the effective thermal conductivity of the lattice geometries that could not be tested.

To this purpose the software Comsol Multiphysics version 5.4 (Comsol Inc. 2018) was used, which is a cross-platform finite element analysis solver and multi-physics simulation software. The Fluid and Heat module was used in a 3D model environment. For the scope of this study, steady-state analysis was performed.

4.6.1 Simulations set-up

Experiment and data

In order to provide accurate boundary conditions for the analysis, geometries, materials, heat transfer physics and boundary conditions were defined. The physics of the problem, combining heat transfer through solid material and through air, was defined in the Heat Transfer module. To include the effect of convective heat flow due to air movements the Laminar Flow module was also introduced. The coupling of the two physics is a non-isothermal flow which refers to fluid flows with variable temperature, where the material properties of the fluid vary according its temperature. The third mode of heat transfer was introduced using the Surface-to-Surface radiation module which can be included in the Multiphysics.

After the first simulation, the Laminar Flow module was put aside due to the high computational cost required for CFD analysis, especially for the shell type geometries. From a theoretical point of view, heat transfer by convection should not give a significant contribution to the overall heat transfer, due to the small size of the cavities. This assumption was verified for one lattice geometry, as discussed in Section 4.6.2.

Geometry

The software allows importing geometries from CAD environments in different formats. Geometries can be imported as solids, breps and meshes while the meshing required by the FE analysis is done directly within Comsol. An important preliminary step involved re-modelling the geometries in a suitable way for the analysis, considering the need to define a geometric domain for the solid material and one for the air around it. The solid material was modelled in the parametric environment of Rhino-Grasshopper, as described above, while the fluid volume is modelled in Rhino using Boolean operations. The air volume is the result of a Boolean difference between the bounding box of the cell and the solid geometry itself (Figure 61).

In order to gain insight on the relation between cell thickness and heat transfer, geometries were modelled with different cell thickness: 1.7 cm, corresponding to the thickness of the printed samples used for physical testing, and 3.4 cm. In both cases, the cell topology is such that the width of the cavities does not exceed 1.5 cm. For each topology, a single cell geometry tested. Moreover, to compare the results of the simulations with those of the physical testing, two PETG 1 mm sheets were also included in the model at the exterior sides.

Materials

COMSOL is equipped with a material database with a specific library for building materials. This was used to define the two materials of the problem, air and PETG, and to assign them to the appropriate domain. Most of the material properties were already set in the database and were left as default while some others, like the thermal conductivity of the PETG, was inserted manually according to the product specifications of the printing filament material (Table 9). For the final simulations (round 6 and 7) air thermal conductivity was substituted with an adjusted value to take into account convection and radiation within air cavities, as explained in Section 4.6.2.6.

Boundary conditions

To simulate the heat transfer between the inside and outside of the room in a winter condition, an ambient temperature of 20°C and an external temperature of 0°C were defined. Two convective heat fluxes through non-solid material were defined at the interior and exterior sides of the geometry, specifying the heat transfer coefficients according to common calculation methods: 7.8 W/m²K for the interior flux and 25 W/m²K for the exterior. The other sides of the geometry were considered to be insulation boundaries, meaning they are adiabatic.

For the Laminar Flow, the compressible fluid option was used and the effect of gravity was included in the calculation. Moreover, the temperature coupling ensured the convective heat flux within the geometry is also affected by the conductive heat transfer.

For the Surface-to-Surface radiation module the surfaces participating in the radiative heat transfer had to be defined as diffuse surfaces. These were assigned an emissivity of 0.85. In order to ensure the coupling with the other heat transfer modes, the temperatures of the surfaces were assigned a dependency on the outcome of the Heat Transfer module. The radiation direction is opacity controlled by default, as the direction and wavelength- dependence does not need to be investigated.

Meshing

The mesh for the geometries was created automatically by the software according to the physics of the problem (Figure 62, 63). The resolution was set to coarse size to get a good trade-off between computation time and accuracy of results.
Solver
Default settings were used for the stationary study solve. The PARDISO solver was used, with a physics controlled tolerance. The solver settings were kept as default.

Probes
In order to retrieve the required results from the analysis, different domain point probes were defined: two points on the external side and two on the internal side as explained for the physical testing (Figure 60). In this way, different temperature values were taken, at points where the solid material is prevalent or where air is dominant. The heat flux was calculated as an average of normal flux entering or leaving the two sides of the geometry.

Results
The outcomes of the analyses could be visualised through temperature distribution graphs which are automatically generated by COMSOL. In order to calculate the effective thermal conductivity of the geometries, the average normal heat flux through the interior and exterior side of the geometry was considered as well as the temperature difference between the interior and exterior surface temperatures, measured at the 4 point probes. The calculation of effective thermal conductivity followed the approach described in Section 4.5.

4.6.2 Simulations overview
The simulations were performed in different steps, in order to evaluate the relations between geometry and heat transfer modes first separately and then combined. In general, simulating a combined heat flow in such complex geometries resulted in a considerable computational cost, increased by the complexity of the geometry and its 3D representation. In the end, it was not possible to combine all the three heat transfer modes in one single model, but some assumptions could be verified.

An overview of the methodology followed for the simulations is presented in Figure 61. Varying parameters such as cell size, cell topology and cell array were introduced to find the best geometrical combination.

1. Conduction in shell and lattice geometries
The first round of simulations was performed to compare the thermal performance of a lattice structure and shell structure in case of sole conductive heat transfer. A cell size of 8 x 8 x 1.7 cm was modelled (Figure 63, 64). This was useful to retrieve some initial values for thermal conductivity and compare the results of the analytical models.

As can be observed in Table 13, the two cells show a considerable reduction in thermal conductivity compared to the solid PETG material ($\lambda = 0.2$ W/mK). The lattice geometry, Star Tetrahedral, shows a very low thermal conductivity and performs better than the shell geometry. Overall, the results approximate those of the hand calculations (Table 9), with $\lambda = 0.035$ W/mK and $\lambda = 0.042$ W/mK for the lattice and the shell geometry respectively. Both the hand calculations and the simulations only take into account the effect of heat transfer by conduction.

![Figure 64: Varying geometrical parameters introduced for the simulations in COMSOL Multiphysics](image)

![Figure 65: Overview of simulations methodology in COMSOL Multiphysics](image)
The simulations however also take into account the topology of the geometries while the relations used in the hand calculations are only based on the porosity of the geometries.

These results are much lower than those of the physical tests (\(\lambda = 0.06 - 0.07\) W/mK), suggesting that the other heat transfer modes give a considerable contribution to the global heat transfer. Considering the expected convection in small size air cavities, heat transfer radiation is most likely to be the missing contribution.

It should also be noted that COMSOL simulations are set for a temperature difference between exterior and interior environment in winter (0-20 °C). However, physical tests were performed at much higher temperatures: 22 °C and 49 °C. The higher temperatures affect results in terms of material properties, as thermal conductivity of air increases with temperature and radiative heat transfer also increases with temperature.

### 2. Conduction in shell and lattice geometries comparing different cell topologies with larger cell thickness

The second round of simulations was performed for all the chosen geometries. A cell size of 8 x 8 x 3.4 cm was used to assess the influence of thickness variation on the heat transfer (Figure 65, 66). A wider cell thickness would allow for a smaller number of cells in the whole panel, thus simplifying the modelling process and the production. Nevertheless, the air cavities were kept within 2 cm to minimise convective heat flows. With these simulations all the geometries could be compared to one another.

The results are shown in Table 14 where the two geometries which were also tested in the first simulation round are highlighted. Compared to the thin cell size, the performance does not change considerably. Both options show an increase of 0.003 W/mK in the thermal conductivity. This can also be caused by the different approach used for retrieving the surfaces temperatures, by averaging the results of the two exterior sides in the first simulation and by considering probe points on the solid and void part of the geometries in the second simulation. Given this small difference, it is reasonable to assume that such change in thickness of the cell will not affect the thermal performance, while being very beneficial for decreasing the overall cell number in the panel. Conductive heat flow is also expected to remain unchanged while radiative heat transfer could also decrease in the thicker cell option, due to the larger surface scattering radiation within the cell. Additional convective heat flow could happen within the bigger size cell which, given the small size of the cavities, should not be significant.

The results also allow to make a comparison between the different geometries. Lattice and shell geometries show a comparable thermal performance. Lattices show a thermal conductivity ranging from 0.020 to 0.029 W/mK. The best performance is from BC star, confirming that a high porosity is beneficial for thermal insulation, while the worst performance is from FC cubic which is also the geometry with the largest number of struts. The thermal conductivity of shell geometries does not vary as much as for lattices and between 0.029 W/mK and 0.033 W/mK.

For this simulation round, the results were calculated using values retrieved from different point probes, as done for the physical testing in order to be able to make a comparison between results. In case of the simulations, the thermal conductivity calculated at the solid points results to be higher than that of the void points, as one would expect. As discussed in Section 4.5, this was not the case for the physical tests. In the light of the simulations results, this could be explained by inaccuracies of the testing tools, such as the thermocouples.
3. Conduction and convection in shell and lattice geometries comparing different cell thicknesses

The third round of simulations aimed at introducing heat transfer by convection in the model, using the Laminar Flow module. However, CFD analysis required high computational time and power, which could not be handled in case of shell geometries, due to the complexity of the geometry. Nevertheless, results could be retrieved for the BC star lattice in two different cell thickness options. Figure 67 and 68 show the results of the simulations in form of temperature distribution and iso-surfaces. From these, it can be observed that air movements within the geometry are relatively small and do not affect the temperature distribution within the cell is not affected. This is also confirmed by the results shown in Table 15: the thermal conductivity of the thick cell only increases by 0.001 W/mK compared to the previous simulation where convection was not considered. This increase could be caused a slightly different mesh resolution for the two simulations.

In order to assess the influence of cell thickness on the convective heat flow a cell of 1.7 cm thickness was also tested. The results show that no large variations occur compared to the bigger size, confirming that a cell thickness of 3.4 cm can be used for the design. Therefore, it could be inferred that the difference between the results of the simulations and the physical tests is caused by the contribution of radiative heat transfer. Form this point on, it was decided to neglect the effect of convective heat flow.

4. Conduction in shell and lattice geometries with PETG sheets

For the fourth round of simulations, two PETG sheets were modelled at the exterior sides of the geometry (Figure 72, 73). In this way, the models could approximate the tested samples and a comparison between the results could be done.

The results presented in Table 16 show that the PETG sheets cause an increase in thermal conductivity for all the different geometries, due to the increased amount of solid material. To speed up the process of data retrieving, the values of inner and outer surfaces temperature were taken as an average on the exterior faces of the PETG sheets. As can be seen in Table 15, the results for shell geometries still fail to match those of the physical tests, confirming that the missing contribution should be caused by radiative heat transfer. Overall, the best geometry is the BC star among lattices and the Gyroid among shells.

5. Conduction and radiation in shell and lattice geometries with PETG sheets

The fifth batch of simulations was aimed at introducing radiative heat transfer coupled with convection in the model. Also in this case the computational power required was very significant. This was especially problematic in case of shell geometries where the effect of multiple reflections between the surfaces had to be calculated. Therefore, the simulations were performed not taking into account the inside geometry and only considering the effect of radiation between the two PETG sheets. This was done for two geometries, a lattice and a shell type, to assess the effect of this simplification (Figure 74, 75).

As can be seen in Table 17, the values of thermal conductivity considerably increase, reaching higher than 0.1 W/mK. Again, the results of the simulations fail to match those of the physical tests. These results suggest that the inner geometry plays a significant role in radiative heat transfer. As can be seen in Table 17, the values of thermal conductivity considerably increase, reaching higher than 0.1 W/mK. Again, the results of the simulations fail to match those of the physical tests. These results suggest that the inner geometry plays a significant role in radiative heat transfer, acting as radiation shield at some points.

### Table 15: Results of COMSOL simulations for BC lattice – conduction only

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Thickness [m]</th>
<th>$T_{in}$ [°C]</th>
<th>$T_{out}$ [°C]</th>
<th>$Q_{in}$ [W/m^2]</th>
<th>$Q_{out}$ [W/m^2]</th>
<th>$R_{tot}$ [W/mK]</th>
<th>$\lambda_{eff}$ [W/mK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC cubic Solid</td>
<td>0.034</td>
<td>20</td>
<td>18.4</td>
<td>0.52</td>
<td>13.7</td>
<td>13.7</td>
<td>0.025</td>
</tr>
<tr>
<td>BC cubic Void</td>
<td>0.034</td>
<td>20</td>
<td>17.6</td>
<td>0.63</td>
<td>13.7</td>
<td>13.7</td>
<td>0.027</td>
</tr>
<tr>
<td>BC cubic Solid</td>
<td>0.017</td>
<td>20</td>
<td>17.2</td>
<td>0.9</td>
<td>23.4</td>
<td>23.4</td>
<td>0.024</td>
</tr>
<tr>
<td>BC cubic Void</td>
<td>0.017</td>
<td>20</td>
<td>16</td>
<td>1.47</td>
<td>23.4</td>
<td>23.4</td>
<td>0.027</td>
</tr>
</tbody>
</table>

Table 16: Results of the simulations, highlighting the best options for lattices and shells – conduction only

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Thickness [m]</th>
<th>$T_{in}$ [°C]</th>
<th>$T_{out}$ [°C]</th>
<th>$Q_{in}$ [W/m^2]</th>
<th>$Q_{out}$ [W/m^2]</th>
<th>$R_{tot}$ [mW/cm²]</th>
<th>$\lambda_{eff}$ [W/mK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gyroid</td>
<td>0.036</td>
<td>20</td>
<td>14.9</td>
<td>1.6</td>
<td>39.3</td>
<td>39.3</td>
<td>0.34</td>
</tr>
<tr>
<td>Tetrahedral</td>
<td>0.036</td>
<td>20</td>
<td>15.4</td>
<td>1.2</td>
<td>35.9</td>
<td>35.9</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Table 17: Results of the simulations, combining conduction and radiation heat flows
6. Conduction and radiation in shell and lattice geometries with PETG sheets, considering and adjusted thermal conductivity for air

The sixth batch of simulations was performed using a simplified model to account for radiation and convection happening in the small air cavities by assigning an adjusted thermal conductivity value to air. The procedure for calculating the adjusted thermal conductivity follows NEN-EN-ISO 6946, which presents analytical methods for the calculation of thermal resistance and transmittance for building components and elements (Europese en mondiale normalisatie klimaatbeheersing, 2008).

This calculation method assumes that airspaces in building components other than glazing can be treated as media with thermal resistance, as the radiation and convection heat transfer across them is approximately proportional to the temperature difference between the bounding surfaces. The calculation was done considering the method proposed for unventilated air spaces with small thickness compared to the other dimensions. The result of this calculation is an adjusted thermal conductivity value to be assigned to air instead of \( \lambda = 0.025 \).

Following NEN-EN-ISO 6946, the thermal resistance of the airspace is given by:

\[
R_g = \frac{1}{h_a + h_r} \quad [26]
\]

where:
- \( R_g \) is the thermal resistance of the airspace in m\(^2\)K/W;
- \( h_a \) is the conduction/convection coefficient in W/m\(^2\)K;
- \( h_r \) is the radiative coefficient in W/m\(^2\)K.

For temperature differences across the airspace exceeding 5K, \( h_a \) is assigned the largest value between conductive and convective heat transfer coefficient. The former is calculated as \( \Phi/\text{thickness} \) while the latter is defined as 0.73*\(|\Delta T|/3\). \( h_r \) depends on the emissivities of the surfaces bounding the airspace according to the following relation:

\[
h_r = \frac{1}{(1/\varepsilon_1 + 1/\varepsilon_2)} \times h_r^0 \quad [27]
\]

where:
- \( \varepsilon_1 \) and \( \varepsilon_2 \) are the hemispherical emissivities of the surfaces and are equal to 0.85 for PETG;
- \( h_r^0 \) is the radiative coefficient for a black-body surface, which is equal to 5.1 W/m\(^2\)K for mean temperatures of 10°C.

In case of lattices and shell geometries the cavity is actually split in two parts by the geometry. Therefore, the calculation was made considering two cavities, interrupted by a solid part, as shown in Figure 76. The final resistance \( R_g \) is the sum of the resistance of the two cavities.

The result of this calculation is an adjusted thermal conductivity value to be assigned to air instead of \( \lambda = 0.025 \).

Following NEN-EN-ISO 6946, the thermal resistance of the airspace is given by:

\[
R_g = \frac{1}{h_a + h_r} \quad [26]
\]

where:
- \( R_g \) is the thermal resistance of the airspace in m\(^2\)K/W;
- \( h_a \) is the conduction/convection coefficient in W/m\(^2\)K;
- \( h_r \) is the radiative coefficient in W/m\(^2\)K.

For temperature differences across the airspace exceeding 5K, \( h_a \) is assigned the largest value between conductive and convective heat transfer coefficient. The former is calculated as \( \Phi/\text{thickness} \) while the latter is defined as 0.73*\(|\Delta T|/3\). \( h_r \) depends on the emissivities of the surfaces bounding the airspace according to the following relation:

\[
h_r = \frac{1}{(1/\varepsilon_1 + 1/\varepsilon_2)} \times h_r^0 \quad [27]
\]

where:
- \( \varepsilon_1 \) and \( \varepsilon_2 \) are the hemispherical emissivities of the surfaces and are equal to 0.85 for PETG;
- \( h_r^0 \) is the radiative coefficient for a black-body surface, which is equal to 5.1 W/m\(^2\)K for mean temperatures of 10°C.

In case of lattices and shell geometries the cavity is actually split in two parts by the geometry. Therefore, the calculation was made considering two cavities, interrupted by a solid part, as shown in Figure 76. The final resistance \( R_g \) is the sum of the resistance of the two cavities.

The results of the simulations are shown in Table 19. It can be observed that lattice geometries behave better than shell geometries, with \( \lambda \) ranging from 0.063 to 0.076 W/mK, and are strongly influenced by the porosity of the geometries. Shell geometries present higher thermal conductivity values with the Gyroid type being the best alternative (\( \lambda = 0.079 \)).

These results are compared to those of the physical tests in Figure 77. A difference of 10% and 22% is found for the Gyroid and Diamond geometry respectively. This difference is small enough to consider the COMSOL model as a reliable one, to be used for further simulations. For the Schwartz’s P geometry, however, this difference increases to 40%. This could be explained by the fact that, contrary to the other two, this geometry was printed with a smaller shell thickness (1 mm instead of 2 mm) as part of the exploration of the manufacturing process. The resulting thermal conductivity from the physical tests would be higher in case the sample was printed with a thicker shell, thus better aligning with the simulations results.

Overall, the results of the simulations prove the reliability of the COMSOL model which is refined enough to approximate the physical heat transfer in cellular structures. The model also allows for a more accurate comparison of the different geometries, as possible inaccuracies in the model would affect the different geometries in the same way. On the contrary, the inaccuracy of the measurements of the physical tests can differ from case to case in an unpredictable way. Therefore, in order to choose the best geometry for further development of the façade panel, the comparison between the different geometries will be based on the simulation results.

Table 18 shows the resulting value \( \lambda = 0.07 \) which was then inserted in the COMSOL model, as property of air material. In this way, a simulation considering the sole conduction heat flux could be performed using the Heat Transfer module. The adjusted thermal conductivity value accounts for the other heat transfer modes.

![Adjusted air thermal conductivity](image)

**Table 18**: Adjusted air thermal conductivity

**Figure 76**: Double unventilated cavity scheme for the calculation

**Figure 77**: Comparison of results from physical tests and COMSOL simulations

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Additional models were generated and simulated to assess the influence of cell size in the heat transfer. Keeping a cell thickness of 3.6 cm, including the presence of two PETG sheets, two different cell sizes were simulated with dimension of 15 cm and 20 cm (Figure 79, 80).

Using a larger cell size would result in a faster production process along with a more effective computational workflow for the generation of the geometry. The results of the simulations presented in Table 21 show that there is nearly no difference between the two options, but both options perform better than the initial geometry with 3.6 x 8.3 x 8.3 cm cell size. This can be explained by the larger gas-to-solid ratio of the elongated cells. As the geometry is generated to adapt to the cell size, larger cavities are created that are effective in reducing the overall thermal conductivity by about 15%.

### Table 19: Results of COMSOL simulations for different cell geometries – using the calculation method from NEN-EN-ISO6946

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Thickness m</th>
<th>$T_1$ °C</th>
<th>$T_2$ °C</th>
<th>$T_w$ °C</th>
<th>$Q_m$ W/m²</th>
<th>$Q_{aw}$ W/m²</th>
<th>$R_m$ [W/mK]</th>
<th>$\lambda_m$ [W/mK]</th>
<th>$\lambda_{aw}$ [W/mK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gyroid</td>
<td>0.036</td>
<td>20</td>
<td>15.9</td>
<td>1.3</td>
<td>0</td>
<td>32</td>
<td>0.46</td>
<td>0.071</td>
<td>0.177</td>
</tr>
<tr>
<td>Diamond</td>
<td>0.036</td>
<td>20</td>
<td>15.8</td>
<td>1.3</td>
<td>0</td>
<td>32</td>
<td>0.44</td>
<td>0.081</td>
<td>0.663</td>
</tr>
<tr>
<td>P</td>
<td>0.036</td>
<td>20</td>
<td>14.4</td>
<td>1.6</td>
<td>0</td>
<td>41.2</td>
<td>0.31</td>
<td>0.116</td>
<td>0.069</td>
</tr>
</tbody>
</table>

### Table 20: Results of COMSOL simulations for different cell array – using the calculation method from NEN-EN-ISO6946

<table>
<thead>
<tr>
<th>COMSOL Heat Transfer with PETG sheets - Adjusted cavity λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Gyroid (3 cells)</td>
</tr>
<tr>
<td>Gyroid (5 cells)</td>
</tr>
</tbody>
</table>

### Table 21: Results of COMSOL simulations for different cell sizes – using the calculation method from NEN-EN-ISO6946

<table>
<thead>
<tr>
<th>COMSOL Heat Transfer with PETG sheets - Adjusted cavity λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>3.6 x 15 x 15 cm</td>
</tr>
<tr>
<td>3.6 x 20 x 20 cm</td>
</tr>
<tr>
<td>3.6 x 25 x 25 cm</td>
</tr>
</tbody>
</table>
Conclusions
Simulation of heat transfer through cellular structures proved to be expensive from a computational point of view, due to the complexity of the geometries involved, particularly for shell topologies. However, through the different steps of the simulation process, some conclusions could be drawn regarding the thermal behaviour of cellular structures:

- **Conduction** and **radiation** contribute to the global heat transfer in equal part in shell geometries. In lattice geometries radiative heat transfer is more significant than conduction (Figure 84);
- When **small air cavities** are involved (up to 2 cm), heat transfer by convection is minimal and can be neglected;
- **Volume-to-surface ratio** is the driving factor for thermal insulation.

The real influence of the inner geometry in radiative heat transfer could not be simulated, however the simplified method described for simulation round 6 proved to be reliable enough to match the physical test results in case of shell geometries. The behaviour of lattice geometries could be better investigated by performing physical tests on 3D printed samples.

Overall, lattices have proved to be more efficient in thermal insulation. As calculated in simulation round 6, the average thermal conductivity of such geometries is 0.07 W/mK which is lower than the average for shell geometries, 0.09 W/mK. This suggests that lattices could be further investigated for their thermal properties.

From a geometrical point of view, the thermal resistance of lattices is greatly dependent on the porosity of the cell structure. The influence of porosity is less predictable for shell structures, where the Schwartz’s P geometry resulted to have a higher thermal conductivity, in spite of its low relative density (Table 22).

In general, differences in results between the geometries are not very significant. Therefore, the choice of the best geometry, to be explored in the façade panel design, should be done by considering both thermal and structural aspects. Finally, the results of simulation round 7 suggest that the use of a cell with a bigger width and height is beneficial for the thermal performance.

<table>
<thead>
<tr>
<th>Cell size (8,3x8,3x3,6 cm)</th>
<th>Strut/Wall [mm]</th>
<th>Relative Density</th>
<th>Thermal Conductivity [W/mK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice BC (star)</td>
<td>Ø2 - 2</td>
<td>0.06</td>
<td>0.063</td>
</tr>
<tr>
<td>Gyroid</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ø2 - 2</td>
<td>0.15</td>
<td>0.074</td>
<td></td>
</tr>
<tr>
<td>Ø2 - 2</td>
<td>0.23</td>
<td>0.074</td>
<td></td>
</tr>
<tr>
<td>Ø2 - 2</td>
<td>0.07</td>
<td>0.072</td>
<td></td>
</tr>
<tr>
<td>Ø2 - 2</td>
<td>0.14</td>
<td>0.064</td>
<td></td>
</tr>
<tr>
<td>Ø2 - 2</td>
<td>0.17</td>
<td>0.064</td>
<td></td>
</tr>
</tbody>
</table>

Table 22: Overview of results of thermal simulations for different cell topologies

References:

Figure 84: Comparison of results from analytical models, physical tests and software simulations
4.7 Simulations in Karamba for Grasshopper

In order to further assess and compare the behaviour of the different geometries, their structural performance was studied using Karamba3D plug-in for Grasshopper (Preisinger, 2018). Karamba3D is a parametric structural engineering tool which provides accurate structural analysis of spatial trusses, frames and shells. Being fully embedded in the parametric design environment of Grasshopper, it is able to combine parameterized geometric models and finite element calculations. For each cell topology an array of 4 x 3 x 2 cells was generated in and analysed under the same load condition.

**Loads**
The different models were analysed under out-of-plane uniformly distributed load, simulating the effect of wind load. Since the aim of the simulation was to compare the behaviour of different cell topologies rather than retrieving specific performance indicators, an arbitrary load of 10 kN/m² was applied.

**Supports**
For each sample, four pinned supports were defined at the four corners, restraining translation along x, y and z-axis.

**Properties**
The material properties used as input for the analysis are derived from the 3D printing filament material specifications, as shown in Table 10 (Section 4.4).

**Results**
The structural analyses were useful to gain insight on the structural behaviour of the different topologies and to evaluate the influence of geometry, which could not be taken into account in the hand calculations. The results of the simulations are presented in Table 23 and can be visualised in Figure 87.

Overall, lattices showed good behaviour in terms of load transfer, resulting in low stresses in the structures. However, the analysis also indicated that some of the lattice types, such as BC Star, FC cubic, Vertex Octahedron and Star Tetrahedral do not have a perfect stretch-dominated behaviour due to their geometry. In this geometries, load is not transferred by sole means of compression and tension but bending moments are also generated, resulting in higher stress states in the struts and worsening the overall structural performance (Figure 85, 82). On the contrary, BC cubic and Tetrahedral lattice types, which are perfectly triangulated geometries, showed a perfect stretch-dominated behaviour with low stress state and minimal deflection.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Max. Stress C (MPa)</th>
<th>Max. Stress T (MPa)</th>
<th>Max. Utilisation T - %</th>
<th>Max. Utilisation C - %</th>
<th>Deflection [m]</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gyroid</td>
<td>56</td>
<td>24</td>
<td>10</td>
<td>24</td>
<td>0.0004</td>
<td>Peak stresses at the unconnected edges (in tension and compression)</td>
</tr>
<tr>
<td>Diamond</td>
<td>155</td>
<td>300</td>
<td>119</td>
<td>64</td>
<td>0.0004</td>
<td>High peak stresses at the unconnected edges (mainly in tension)</td>
</tr>
<tr>
<td>P</td>
<td>13</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>0.0001</td>
<td>Peak stresses at the unconnected edges (mainly in tension)</td>
</tr>
<tr>
<td>Lattices</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BC Star</td>
<td>403</td>
<td>300</td>
<td>127</td>
<td>171</td>
<td>0.0566</td>
<td>Not rigid structure. Great deformation. Bending is allowed</td>
</tr>
<tr>
<td>BC cubic</td>
<td>33</td>
<td>28</td>
<td>12</td>
<td>14</td>
<td>0.0007</td>
<td>High peak stresses on the diagonals in the supported cells</td>
</tr>
<tr>
<td>FC Cubic</td>
<td>66</td>
<td>57</td>
<td>24</td>
<td>28</td>
<td>0.0015</td>
<td>Bending is allowed. Great stress on diagonals at the sides of the array</td>
</tr>
<tr>
<td>Vertex Oct</td>
<td>43</td>
<td>24</td>
<td>10</td>
<td>18</td>
<td>0.0070</td>
<td>Bending is allowed. Very high peak stresses</td>
</tr>
<tr>
<td>Star Tet</td>
<td>79</td>
<td>76</td>
<td>32</td>
<td>34</td>
<td>0.0025</td>
<td>Bending is allowed. Peak stresses on diagonals at the supported edges</td>
</tr>
<tr>
<td>Tetrahedral</td>
<td>28</td>
<td>21</td>
<td>8</td>
<td>12</td>
<td>0.0007</td>
<td>High stresses on vertical beams at the sides of the geometry</td>
</tr>
</tbody>
</table>

Shell geometries proved to have exceptionally high stiffness and undergo small deflections. Stress values are generally higher than those found in triangulated lattices and peak stresses develop at the unconnected edges at the corners of the cells. The Schwartz’s P shell geometry stands out for its results, showing minimal deflection and very low stress state. It should be noted that, due to their thin-walled geometry, shells are likely to undergo failure by buckling. Estimating the buckling load for thin-walled shells is not an easy task, especially if complex geometries are involved. Nevertheless, when assessing the overall structural performance this occurrence should be taken into account.
4.8 Simulation in COMSOL Multiphysics

Through the simulations in COMSOL and Karamba-Grasshopper, it was possible to understand how the different cell topologies behave in heat and load transfer. With respect to the hand calculations, the influence of cell topology on the behaviours was found to be very significant, especially for the structural performance, leading to a significant diversity in behaviour among geometries that have comparable relative density.

Although the performance of the geometries could be further explored by refining the models and set-up of the simulations, sufficient information was retrieved to assess the different options and choose the best alternative to further explore for the façade panel design.

As shown in Table 24, structural and thermal performance indicators for the different geometries point towards different alternatives. The best lattice geometries in terms of thermal performance, Star Tetrahedron and BC, are the worst options from a structural point of view. At the same time, the best cell geometry in terms of structural performance, Schwartz’s P, is the one with highest effective thermal conductivity. These results suggest that no geometry combines optimal thermal and structural performance at the same time.

It would be interesting to further investigate the relation between geometry and performance and proceed to a manipulation of the cell topology in order to obtain optimal results for structural and thermal behaviour. This, for example, could be done in case of lattices by modifying number and orientation of the struts or in case of shell geometry by varying the porosity of the cell and the connectivity between cells. A multi-objective optimisation could be set up to this purpose, integrating the structural and thermal indicators, with the aim to minimise thermal conductivity, deflection and stress in the geometry. This, however, goes beyond the scope of this research and, therefore, the choice of the most suitable geometry for the façade panel was taken with a trade-off between the two objectives.

Table 24: Overview of results for different cell topologies – the best performing geometries are highlighted.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Cell size (8,3x8,3x1,5cm)</th>
<th>Strut/Wall ratio</th>
<th>Relative Density</th>
<th>Thermal conductivity (W/mK)</th>
<th>Max deflection [m]</th>
<th>Deflection [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star Tetrahedron</td>
<td>Ø2 - 2</td>
<td>0,06</td>
<td>0,963</td>
<td>171</td>
<td>0,0366</td>
<td>28</td>
</tr>
<tr>
<td>Vertex Octahedron</td>
<td>Ø2 - 2</td>
<td>0,15</td>
<td>0,074</td>
<td>0,0015</td>
<td>0,0001</td>
<td></td>
</tr>
<tr>
<td>Tetrahedral</td>
<td>Ø2 - 2</td>
<td>0,23</td>
<td>0,076</td>
<td>28</td>
<td>0,0016</td>
<td></td>
</tr>
<tr>
<td>Gyroid</td>
<td>Ø2 - 2</td>
<td>0,07</td>
<td>0,072</td>
<td>18</td>
<td>0,0050</td>
<td></td>
</tr>
<tr>
<td>Diamond</td>
<td>Ø2 - 2</td>
<td>0,14</td>
<td>0,061</td>
<td>38</td>
<td>0,0069</td>
<td></td>
</tr>
<tr>
<td>Schwartz’s P</td>
<td>Ø2 - 2</td>
<td>0,17</td>
<td>0,066</td>
<td>12</td>
<td>0,0007</td>
<td></td>
</tr>
</tbody>
</table>
In case of lattices, the best alternative appears to be the Tetrahedral type, which combines good thermal performance, with thermal conductivity of 0.068 W/mK and the best structural performance compared to the other lattice types. As regards shell geometries, the Schwartz’s P type which is by far the best alternative from a structural point of view, cannot be chosen due to the high thermal conductivity resulting from the simulations. The Gyroid type can be considered as the best alternative, with the lowest thermal conductivity and good results in terms of stress and deflection.

Figure 88: Chosen topologies according to the results of the research through design exploration: Tetrahedral lattice and Gyroid Shell

4.9 Lattice and shell geometries compared

A further step in the evaluation of the different alternatives is the comparison of the lattice and shell types. Overall, the results of the simulations indicate that similar values can be obtained, making it hard to assess which one performs best overall. In general, lattice types are widely used in engineering due to their lightweight. In case of a façade element, weight is an important parameter and a lower weight can result in a decrease in material usage not only for the panel itself, but also for the load bearing structure. The thermal and structural performance of lattices makes them interesting to explore for façade applications as the one being explored in this study. On the other hand, shell geometries are denser per se and their porosity significantly depends on the capabilities of the production process (e.g. minimum achievable thickness of the shell).

As explained in Section 4.4, the most appropriate AM process for the two geometry types differs. Traditional FDM technique is very much suitable for the production of shell geometries, especially considering the continuity of the nozzle path in printing and the restriction in terms of maximum overhang span. On the contrary, FDM with horizontal slicing is not appropriate for the production of lattice structures and a multi-plane extrusion process is preferable.

In the prospective of producing a prototype of the façade component, the production process for the different geometries is an important aspect to account for when choosing which geometry should be further developed. Considering the currently available tools offered by LAMA, the laboratory for additive manufacturing in architecture at the TU Delft Faculty of Architecture and Built Environment, multi-plane extrusion process cannot be implemented. Therefore, prototyping a lattice-based geometry would require the use of external facilities to the university. In the light of these aspects, the shell Gyroid geometry was chosen for the design. However, it should be remarked that lattice geometries appear to be very promising for application in the building envelope and, therefore, they will also be considered for the next step of the design.

<table>
<thead>
<tr>
<th>Lattices</th>
<th>Thermal Performance</th>
<th>Structural Performance</th>
<th>Weight Reduction</th>
<th>Additive Manufacturing</th>
<th>Additional Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low values of thermal conductivity achievable. Effect of radiation needs further exploration.</td>
<td>Perfectly triangulated geometry result in an efficient structural behaviour in terms of strength and stiffness.</td>
<td>High porosity of lattices results in lightweight components, with reduction in size of the support structure.</td>
<td>Horizontal slicing is not possible; multi-plane extrusion using robotic arm and dedicated cooling fan is necessary.</td>
<td>Porosity would allow the integration of additional elements in the structure.</td>
</tr>
<tr>
<td>Shells</td>
<td>Low values of thermal conductivity achievable. Thickness of the shell is an important variable.</td>
<td>Stiff geometries can be designed, which benefit from the possibility of transferring load in different directions.</td>
<td>Although relative density is higher, weight reduction compared to traditional systems can be achieved.</td>
<td>Suitable for traditional FDM, printing time can be optimised by making sure the path of the extruding nozzle is continuous.</td>
<td>Open cell structures have better acoustic insulation behaviours and cushioning characteristics.</td>
</tr>
</tbody>
</table>
In the Component Design phase a façade element was designed following a performance-driven approach. First, the procedures used for the generation of the element geometry, integrating the guidelines discussed in the Chapter 4, are discussed. The final design is presented along with the validation of its structural performance. The outcome of the process includes the definition of a digital workflow which can be used as a digital tool. The results of the prototyping phase are presented and the feasibility of the production with AM is discussed. Finally, the potential application of the AM envelope component are explored and direction for further development of the design are proposed.
5.1 Strategy
The last phase of this study was aimed at implementing the outcomes of the Research through design exploration for the design of the façade panel. This was done by combining the results of topology optimisation and geometry exploration (Figure 88). Different strategies were elaborated for this purpose, considering the implementation of both lattice and shell geometry types. The final component was validated for structural usability and safety through FE analysis. According to the results, the design of the panel was iteratively improved by increasing the cell size in order to decrease weight and relative density.

As a result of the study, a parametric computational work-flow is proposed which could be implemented to design a façade panel with density-graded cellular geometries to combine thermal and structural performance.

5.2 Choice of façade support system
The first step in the elaboration of the final design was the choice of the appropriate support system among the options proposed in Section 4.2. The results of topology optimisation were evaluated according to three main parameters: relative density compared to the initial boundary volume, potential for integration of additional functionalities for the building envelope and applicability in terms of façade technology.

Option 1 corresponds to a four-point support condition, which can be achieved with the integration of metal brackets transferring the structural loads to the supporting slabs of the building. A simple system as such would allow a diverse range of application as each panel is independent. The resulting optimised topology opens up the possibility to integrate a transparent component on the upper part. Moreover, the less dense area on the bottom part could be designed for an improved thermal insulation so as to create a gradient of Rc-values following the vertical temperature distribution within a room.

Option 2 corresponds to a curtain wall support condition, where the panel is supported by brackets on the top part and rests on the panel below at the bottom. In this case, the implementation of the panel requires a façade system. The less dense area on the upper part suggests the integration of a transparent component.

Option 3 corresponds to a support system where two linear frames transfer the loads from the panel to the supporting structure. This option could also be implemented if the supporting structure lies on the façade line: in this case metal frame could rest on top and bottom of the slabs, like in a metal stud wall.

According to the results of the optimisation, Option 1 looks like an interesting alternative to explore, both for the possibility of integration in the building envelope and for the low relative density required.

Regarding the structural behaviour of this topological result, stress and deflection in the model can be considered. Since the topology optimisation algorithm does not consider the properties of the material, only qualitative assumptions can be derived about the structural behaviour. Looking at the principal stress lines (Figure 94), it can be observed how forces flow to the four corners of the panel, where the supports are located. At these points, the highest stresses are concentrated along with the elements with highest prescribed density. Looking at the deflection in the panel (Figure 93), the middle part of the panel undergoes maximum deflection under the wind load. The exact values for stress and deflection are calculated in Section 5.3 through FEA analysis.
5.3 Overlapping TO results and cell geometry

The result of topology optimisation is a list of relative density values required by the structural model. The base geometry at cell level needs to adapt to those values in order to best serve the panel’s structural requirements. Different strategies were elaborated for this geometry grading using computational tools.

Grading based on prescribed density value

The first strategy consists in using the prescribed density value for each finite element resulted from the topology optimisation to assign thickness value to the cell geometry. Since the number of FE generated for the topology optimisation does not correspond to the number of voxels composing the façade panel, the influence of this values should be based on the distance between the finite element and the voxel. Therefore, besides the prescribed density values, the position of the centroid of the finite element is important parameter to be used. This strategy can be developed in a different way for lattices and shells, according to the production process. In particular, in case of shells the thickness of the geometry can be controlled while in case of lattices the radius of the struts can be controlled. In both cases, the most appropriate manufacturing strategy would be extrusion through nozzles of different width.
Grading voxelisation resolution based on prescribed density value

An alternative strategy is using the results from the topology optimisation as a parameter to change the size of the voxel to which the geometry is applied. In this way, voxel of different size can be generated creating high-stiffness areas within panel where additional density is required. Figure 88 shows a visualisation of the panel modelled according to this strategy. For simplicity, only two voxel sizes were defined changing width and height with constant thickness. The dimensions are such that the big voxel corresponds to four small voxels.

Difficulties in the production of such geometries are related to the need of connecting the geometries created within the voxels. While in lattices this can easily be achieved, connection of shell geometries of different size is troublesome due to the small number of contact points. Nevertheless, continuity of the geometry is required by the production process and, at the same time, is beneficial for the stiffness of the panel. Therefore, in case this strategy is adopted, the cell geometry should be modified to allow for connection between cells.

Morphing voxel grid according to attraction points

The third strategy is based on the idea of considering the results of topology optimisation as a field of attractor points according to which the regular voxel grid can be deformed. The challenge of this strategy is ensuring that the voxels maintain their adjacency after the morphing so that continuity of the geometry can be assured.

To do this, dynamic relaxation can be used, which is a numerical method based on the discretization of the continuum into a set of concentrated masses (particles) linked by elements (springs) defining how forces and moments propagate through the system (Senatore & Piker, 2015).

The particle-spring mode was set up in such a way that the spring length is controlled by the density map resulting from topology optimisation. A list of attractor points among the list of centroids for each finite element was selected, according to their prescribed density. Only voxels whose prescribed density is higher than the average value were selected. The centroids of the selected voxels are used as attractor points and the length of the springs in the dynamic relaxation model changes according to the distance between its end points (particles) and the attractor points. In this way, the voxel are deformed so that their dimension increases with distance from the attractor points, creating denser voxel resolution in the panel corresponding to high-density areas (Figure 98).

Although more demanding from a computational point of view, this strategy results to be the most effective in relating the density map derived from the topology optimisation and the cell geometry, ensuring the connectivity of the cells is maintained. This strategy is would be preferable in case of shell geometry, whereas the first strategy of grading the radii of the struts is the most straight-forward approach in case of lattice geometries.
5.4 Structural Performance of façade component

FEA analysis was performed to assess the structural performance of the façade panel and verify the effectiveness of the density grading strategy by comparing the results of the ungraded geometry with those of the graded one.

Limit values

Usability was verified comparing the maximum deflection in the panel to the maximum value allowed. The validation was done according to CEN – EN 13830 which is a European Standard specifying requirements of curtain walling kit intended to be used as a building envelope. The standard applies to components fulfilling its own integrity and mechanical stability but not contributing to the load bearing or stability of the main building structure, and could be replaced independently of it. Safety was verified with a preliminary assessment to check whether the maximum stresses in the structure exceed the yield strength of the material. The norm prescribes that, under the imposed winds, the maximum frontal deflection of curtain walling’s framing members of length L shall not exceed 5 mm+ L/300, if 3000 mm< L < 7500 mm. This limit has been considered for the entire façade panel and is set to 15 mm.

Since polymers are characterised by brittle failure, the maximum stress criterion is used for verification of usability. According to this, failure occurs when the maximum principal stress (σ1 or σ2) reaches either the uniaxial tension strength (σt) or the uniaxial compression strength (σc). Therefore, the following condition should be verified:

$$\sigma_c < \min\{\sigma_1, \sigma_2\} < \sigma_t$$  \[28\]

Considering the geometry of the panel, which is created by repetition of thin-walled cells, failure by buckling is most likely to happen. This could happen at a stress level which is below that which would cause failure of the structure. To take into account this failure mode, a safety factor of 0.7 is applied to the tensile strength of the structure. In this way the stress limit for the material is not 23 MPa, as shown in the technical data sheet, but 16.1 MPa. The analysis was performed within the parametric design environment of Rhino-Grasshopper using Karamba3D plug-in. The model set-up is described below.

Elements

The input geometry for the analysis was the mesh generated in the parametric model. This was analysed as shell element, being a three-dimensional solid with small thickness compared to the other dimensions. Two different models were compared, corresponding to a panel with a uniform geometry and a panel with a density-varying geometry.

Material Properties

For the material properties, data provided by the 3D printing filament producer Innofil3D bv was used (See Appendix). Mechanical properties are retrieved from a uniaxial tensile test for specimen printed vertically along z-axis and horizontally along x,y-axis. By taking into account the values for vertically printed samples, the material properties have been defined as isotropic. The following values have been input:

- Tensile strength: 23 MPa;
- Young’s Modulus: 2140 MPa;
- Density: 1.34 g/cm$^3$

Cross section

A cross section of 1.5 mm is defined with the material specifications described above, corresponding to a single shell thickness for the printed geometry. This effective cross sectional area takes into account the irregularities in the cross section found in 3D printed samples. Measurements done on different geometry samples printed with the same nozzle thickness of 1.7 mm show a non-uniform cross section thickness along the geometry, ranging from 1.5 to 2 mm (Figure 100). For the structural validation a conservative approach was used and the minimum thickness found in the printed samples was used.

References:

**Loads**

Two load cases are applied to the façade: out-of-plane wind load acting along y-axis and gravity load. A wind load of 1 kN/m² is considered, with a resultant force of 4.5 kN.

**Supports**

The panel is supported at the four corners on several mesh points. Translation along x, y and z-axis is constrained, while rotations along the three directions are allowed.

**Results and conclusions**

The results of the simulation are shown in Table 26. Overall, the morphed geometry exhibits a better structural behaviour than the regular geometry. As far as deflection is concerned, both panels exhibit high stiffness, with a maximum deflection in the middle of the panel in the range of 3 mm. Usability on the contrary is more critical as compressive stresses in the structure are found to be close to the material limit. In particular, compressive principal stress exceeds the material limit of 23 MPa in the regular geometry. Detailed results of the FE analysis can be found in the Appendix E.

It is interesting to look at the principal stress trajectories in the two principal directions (Figure 101). These show the characteristics of the stress field within the structure, suggesting how loads flow in the façade panel. It can be observed that the stress trajectories match the results of topology optimisation as they flow from the middle of the panel to the four supported corners. This further confirms the validity of the chosen density grading strategy and the topology optimisation process.

In general, it should be noted that the geometry of the panels gives them exceptional stiffness, resulting in very small deflection. This results from the relatively large thickness of the panels (30 cm) which is required to meet an Rc-value of 4.5 m²K/W. Nevertheless, the result suggests that the geometry can be optimised further to work within the structural limits.

---

**Table 26: Results of FE structural analysis for regular and morphed panel**

<table>
<thead>
<tr>
<th>Gyroid Cell</th>
<th>Principal Stress 1 (MPa)</th>
<th>Principal Stress 2 (MPa)</th>
<th>Deflection [m]</th>
<th>Usability unity check</th>
<th>Safety unity check</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular 15 x 15 x 3,4 cm</td>
<td>-17,1</td>
<td>8,5</td>
<td>0,003</td>
<td>5</td>
<td>0,94</td>
</tr>
<tr>
<td>Morphed 15 x 15 x 3,4 cm</td>
<td>-13,1</td>
<td>5,8</td>
<td>0,003</td>
<td>5</td>
<td>1,23</td>
</tr>
</tbody>
</table>

**Gyroid Cell**

Ultimate Strength [MPa] 23
Safety Factor [-] 0,7
Allowable Stress [MPa] 16,1
Maximum Span [m] 3
Allowable Deflection [m] 0,015

Limit CEN – EN 13830 5 mm + L/300

**Figure 99:** FEA model set-up: loads in orange, supports in blue

**Figure 100:** Measured cross section thickness on 3D printed panel

**Figure 101:** FEA results – Principal stress trajectories on façade panel
5.5 Final Design

Refinement of cell size

According to the results of the structural analysis presented in Section 5.4, the façade panel exhibits high stiffness and maximum deflection in the panel is limited to small values. In order to optimise the overall design, the panel was redesigned with an increased cell size, 25 x 25 x 3.4 mm, achieving a more porous geometry. The relation between cell size and relative density is shown in Figure 102 and depends on the implicit surface equation defined for the gyroid cell:

\[ \cos(x) \sin(y) + \cos(y) \sin(z) + \cos(z) \sin(x) = 0 \]  \[29\]

As can be seen in Table 27, increasing the cell dimension reduces the number of cell needed to fill the panel volume. Moreover, since porosity slightly increases along with the cell size, the weight of the panel can be reduced of more than 8%. Increasing the cell size is also beneficial from a production point of view as printing time is decreased. Considering the thermal performance, simulations presented in Section 4.6 show that increasing the cell size is beneficial as the relative density decreases. In fact, the thermal performance of the panel benefits from the lower thermal conductivity of air.

<table>
<thead>
<tr>
<th>Gyroid Cell size</th>
<th>Voxel volume [m³]</th>
<th>Voxel n° [±]</th>
<th>Cell volume [m³]</th>
<th>Weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3 x 6.3 x 3.4</td>
<td>0.0002</td>
<td>492</td>
<td>21</td>
<td>138,5</td>
</tr>
<tr>
<td>15 x 15 x 3.4</td>
<td>0.0008</td>
<td>1400</td>
<td>59</td>
<td>110,7</td>
</tr>
<tr>
<td>25 x 25 x 3.4</td>
<td>0.0021</td>
<td>504</td>
<td>150</td>
<td>101,3</td>
</tr>
</tbody>
</table>

Table 27: Weight of façade panel according to cell size

Thermal performance

In order to verify the assumption stated above, new simulations were carried out on the bigger cell size geometry in COMSOL. For the simulation, the same set-up described in Section 4.6.1 was used. An effective thermal conductivity for air was assigned to the material to account for radiative and convective heat transfer, according to NEN-EN-ISO 6946. The calculated effective thermal conductivity value equals 0,07 W/mK.

The results of the calculation are shown in Table 28 and Figure 103. As expected, the thermal conductivity of the sample slightly decreases, reaching 0,065 W/mK. In order to achieve the prescribed Rc-value of 4,5 m2K/W the façade panel is required a thickness of 29 cm. This is an additional factor decreasing the overall weight of the panel.

<table>
<thead>
<tr>
<th>Gyorid Cell size</th>
<th>3,6 x 25 x 25 cm</th>
<th>0,036</th>
<th>20</th>
<th>16,6</th>
<th>1</th>
<th>0</th>
<th>28,1</th>
<th>28,1</th>
<th>0,56</th>
<th>0,065</th>
</tr>
</thead>
</table>

Table 28: Results of the simulation in COMSOL Multiphysics

Structural performance

For assessing the structural performance, a FE analysis was performed for the new panel. The results presented in Table 29 show that the structural behaviour of the regular geometry is worse compared to the initial geometry. In particular, deflection doubles compared to the previous model, reaching 0,6 cm. This value is still within the limit set by to CEN – EN 13830. The principal stress in the panel also increases in the regular geometry, reaching 13,9 MPa which still complies with the material limit. On the contrary, the morphed geometry shows a considerable improvement both in terms of deflection and in terms of stress. Maximum deflection in the morphed panel 3 mm, which is five times smaller than the allowed value. Stress is a more critical indicator, especially in compression where maximum values approach the material limit. Nevertheless, it should be noted that the maximum values correspond to peak stresses developing in the panel at the supports, while the average stress values are much lower. The detailed results of the FE analysis can be seen in Appendix E.
The final design is a façade element of 3 x 1.5 x 0.29 m, in which geometry is morphed to provide additional stiffness for the most stressed parts and porosity increased in the less stressed parts improving thermal insulation (Figure 105). The geometry varies also within the panel thickness according to address the required performance using the same material (Figure 106). According to the structural and thermal analysis performed on the element, the component is able to comply with the current regulations regarding maximum deflection and Rc-value.

![Figure 105: Final design of the façade component](image-url)
Figure 106: Section through the façade component showing the varying geometry

Figure 107: Vertical Section through the façade component
As outcome of this study a digital work-flow was defined for designing façade elements with complex geometries for thermal and structural performance. This can be used as a design tool through which the form of envelope components can be generated, according to loads acting on the façade and desired cell geometry.

The geometry generated in the parametric model was analysed with FE methods using a stand-alone software, COMSOL Multi-physics, and Karamba-3D plug-in for Grasshopper. In the last phase of the study, the results of the simulations in COMSOL were analysed and compared to the analytical models in order to find a simple analytical expression for the calculation of effective thermal conductivity which could be integrated within the parametric model.


The same model was also used to generate sample geometries for additive manufacturing which were then tested for the thermal performance. The structural performance of the final geometry was then assessed using Karamba3D for Grasshopper.

Figure 109 provides an overview of the digital work flow, which integrates the exploration done at material meso-scale (cell structure) and macro-scale (component). At the material meso-scale, the script integrates procedures for generation and performance assessment of both shell and lattice geometries. At the component scale, for ease of use in the design process, the script is designed specifically for shell geometries to be produced with FDM. However, this could easily to adapted to lattice geometries with minimal changes in the Geometry morphing phase.

In the figure, the user input, main output for each block and optimisation parameters are highlighted. The input needed includes the choice of cell topology for lattice and shell geometries and the definition of the cell dimension. Moreover, the properties of the chosen material have to be defined for the structural and thermal analyses. Moving to the component scale, the user is required to input the design space which could be a referenced geometry in Rhino or be defined directly within Grasshopper. The same has to be done for supports and load geometries. Moreover, the intensity of the wind load acting on the façade panel needs to be input. Additional geometrical/topological information needs to be defined by the user such as: chosen cell size and topology, and mesh thickness for the final component which corresponds to the layer width in the Fused Deposition Modelling production.

The main output for each phase are: shell topology, defined using the implicit surface equation, to be added to the library of cellular structures (A); cell-array geometry, to be used as input for the structural analysis and for 3D printing of geometry samples (B); effective thermal conductivity, resulting from the analytical expressions defined in this study (C); results of FE structural analysis for lattices, including deflection (D) and material utilisation (E); results of FE structural analysis for shells, including deflection (F) and material utilisation (G); resulting geometry from Topology Optimisation to be used for visualisation (H); the density map which is a visualisation of the prescribed elemental densities from topology optimisation (I); list of voxels defining the design space (J); morphed voxel grid resulting from dynamic relaxation (K); morphed panel geometry to be used for visualisation and as input for the structural analysis (L); panel geometry for AM to be converted to .STL file and sliced for production with FDM (M).

The main optimisation parameters regard topology optimisation and dynamic relaxation. This can be tweaked by expert users or left as default. In the next sections, additional information about the different steps in the digital work-flow can be found, including the plug-ins and components employed.
**Geometry generation**

The generation of the cell geometry is the first step in the digital workflow. This involves the use of Crystallon plug-in for Grasshopper (Porterfield, 2018). This plug-in has the capability of generating lattice structures within Rhino’s design environment, without exporting to a third-party software, and taking advantage of the parametric tools of Grasshopper. The geometry is generated by defining a voxel, or boundary cell, to which a unit cell topology can be applied. The plug-in offers a predefined library of cell topologies for lattices and shells which can also be extended with additional geometry types. Given the limited number of available options for shell geometries, the topology library was extended. To this purpose, the Triply Periodic Surfaces (TPS) chosen for exploration, Schwartz’s P, Gyroid and Diamond, are modelled using the corresponding implicit surface definition. The generation of the geometry involves creating a three-dimensional array of points for evaluating the implicit surface function. The geometry can then be visualised as isosurface, representing points of constant value within the cell volume (Figure 110). Once all the geometries are defined in the topology library, lattice and shell types are generated as curves and mesh respectively. In order to evaluate their geometrical properties, lattice curves are used to generate three-dimensional struts and the shell meshes are extruded as solid geometries (Figure 111). The geometry generated can be used to perform analytical calculations on the thermal performance.

![Figure 110: Digital workflow: TPS geometry generation](image)

**Figure 110:** Digital workflow: TPS geometry generation

Finally, the same script is used to generate cell-array geometries to be 3D printed and tested and to be analysed using FE structural analysis. This is done by defining the boundary volume of the samples and by generating an array of cells into which the shell and lattice geometry is morphed (Figure 112). Before exporting to .STL format, the properties of the output meshes need to be tested, in order to check that the geometry is solid, non-manifold and contains no naked edges. In this phase, the geometry is refined using Weaverbird plug-in for Grasshopper (Piacentino, 2009), particularly for smoothening the mesh division, creating closed meshes and offsetting.

![Figure 111: Digital workflow: Cell topology generation](image)

**Figure 111:** Digital workflow: Cell topology generation

**Thermal analysis**

As explained in Chapter 4, the study of heat transfer in cellular geometries is a complex one. The comparison between the results of analytical models and software simulations has shown that analytical models are not able to account for convective and radiative heat transfer. Finite element analysis has proved to be a powerful tool to estimate the thermal insulation property of cellular geometries. However, the use of a stand-alone software, outside the parametric environment of Rhino-grasshopper, resulted in the impossibility of integrating the results directly in the design process. To overcome this, a the results of the software simulations and analytical models were compared and an analytical expression was proposed to retrieve effective thermal conductivity for cellular structures. In particular, two different expressions are proposed for lattice and shell topologies respectively. In particular, these expressions are derived from the analytical models presented in Chapter 02 and are adjusted in order to account for radiative and convective heat transfer. This is done following the procedure presented in Section 4.6.2, according to the methodology of NEN-EN-ISO 6946, which consists in assigning a new thermal conductivity value to air.

In particular, for lattice structures the model proposed by Ashby (2006) is used, which assumes that, in such geometries, 1/3 of the struts of the cellular structure lie parallel to one Cartesian axis, as presented in Section 2.1.4 (Equation 9). The expression, including the adjusted thermal conductivity value for air ($\lambda_g$), is:

$$\lambda_{cell} = \frac{2}{3} \left( \frac{\rho_s}{\rho_g} \right) \lambda_s + \lambda_g$$

where:
- $\lambda_s$ is the thermal conductivity of the bulk material [W/mK];
- $\lambda_g$ is the adjusted thermal conductivity of air [W/mK];
- $V_s$ is the volume of the bulk material [m$^3$];
- $V_g$ is the volume of air [m$^3$];

For shell topologies, the model developed by Leach (1999) is used instead, which unifies the results of a number of approaches to calculate the conductivity of a cellular structures (Equation 16). The expression, including the adjusted thermal conductivity value for air ($\lambda_g$), is:

$$\lambda_{cell} = \frac{1}{3} \left( \frac{\rho_s}{\rho_g} \right) \lambda_s + \left[ 1 - \left( \frac{\rho_s}{\rho_g} \right) \right] \lambda_g$$

where:
- $\lambda_s$ is the thermal conductivity of the bulk material [W/mK];
- $\lambda_g$ is the adjusted thermal conductivity of air [W/mK];
- $\rho_s$ is the density of the bulk material [kg/m$^3$];
- $\rho_{cell}$ is the density of air [kg/m$^3$];

The calculation of the adjusted thermal conductivity follows the method described in Section 4.6.2 using Equation 26 and 27.

![Figure 112: Digital workflow: Cell-array generation](image)

**Figure 112:** Digital workflow: Cell-array generation
The two expressions have been compared to the results of the software simulations and proved to be relatively accurate. In particular, as presented in Table 30, for lattice topologies a mean approximation error of 10% was found while for shell topologies this accounted for 16%. By looking at the results in Figure 113, it can be noticed that the analytical results do not fluctuate much, giving very similar results for different topologies. This is a limitation in case these analytical expressions have to be used within the digital workflow as objective functions for an optimisation of the geometry. The limited range of values would result in a great design freedom, limiting the possibilities of the optimisation process.

Another approach to retrieve an appropriate analytical expression for thermal conductivity is regression analysis. In particular, the relationship between effective thermal conductivity and cell porosity can be estimated by the linear function:

\[ y = -0.1347x + 0.1888 \]  

where:

- \( x \) is the porosity of the cell topology;
- the two parameters represent the thermal properties of the solid and gas components.

As can be observed in Figure 114, this relation is accurate for all cell topologies except for the Schwartz’s P geometry; further investigation on this aspect is needed. A possible explanation for this is the fact that this particular shell topology is the only one featuring closed air bubbles, which may require further refinement of the model created in COMSOL Multiphysics. For the same reason, a considerable discrepancy between the results of the physical test (0.069 W/mK) and those of the simulations (0.116 W/mK) was found for the same cell topology.

Nevertheless, the two analytical expressions described above were found to be useful and accurate enough to be integrated and used within the digital workflow as a preliminary assessment tool for thermal performance. Figure 115 shows how the two expression have been integrated in the workflow. The user is required to input the material properties of the geometry, while relative density and porosity come as output of the geometry generation part.

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Relative Density</th>
<th>Porosity</th>
<th>Analytical Thermal Conductivity (W/mK)</th>
<th>Software Thermal Conductivity (W/mK)</th>
<th>( \lambda_{\text{Sol}} )</th>
<th>( \lambda_{\text{Gas}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BC (star)</td>
<td>0.06</td>
<td>0.94</td>
<td>0.070</td>
<td>0.063</td>
<td>0.19</td>
<td>0.07</td>
</tr>
<tr>
<td>BC cubic</td>
<td>0.15</td>
<td>0.85</td>
<td>0.049</td>
<td>0.074</td>
<td>0.19</td>
<td>0.07</td>
</tr>
<tr>
<td>PC cubic</td>
<td>0.23</td>
<td>0.77</td>
<td>0.068</td>
<td>0.076</td>
<td>0.19</td>
<td>0.07</td>
</tr>
<tr>
<td>Vertex Octa</td>
<td>0.07</td>
<td>0.93</td>
<td>0.070</td>
<td>0.072</td>
<td>0.19</td>
<td>0.07</td>
</tr>
<tr>
<td>Star Tetrahedron</td>
<td>0.14</td>
<td>0.86</td>
<td>0.049</td>
<td>0.064</td>
<td>0.19</td>
<td>0.07</td>
</tr>
<tr>
<td>Tetrahedral</td>
<td>0.17</td>
<td>0.83</td>
<td>0.049</td>
<td>0.068</td>
<td>0.19</td>
<td>0.07</td>
</tr>
<tr>
<td>Cellular</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gyroid</td>
<td>0.19</td>
<td>0.81</td>
<td>0.094</td>
<td>0.079</td>
<td>0.19</td>
<td>0.07</td>
</tr>
<tr>
<td>Diamond</td>
<td>0.27</td>
<td>0.73</td>
<td>0.104</td>
<td>0.081</td>
<td>0.19</td>
<td>0.07</td>
</tr>
<tr>
<td>Schwartz’s P</td>
<td>0.25</td>
<td>0.75</td>
<td>0.102</td>
<td>0.116</td>
<td>0.19</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Table 30: Comparison of analytical model and software simulation results
Structural analysis

The cell arrays generated are studied using Karamba3D plug-in for Grasshopper (Preisinger, 2018). Shell topologies are analysed as shell defined by a mesh while lattice topologies are analysed as beams represented by 2D lines. For both geometries a uniformly distributed out-of-plane load is defined. Since the analysis is aimed at comparing the structural behaviour of the different geometries rather than retrieving specific performance indicators, an arbitrary load of 0.1 KN/m$^2$ is applied.

The first part of the script retrieves the appropriate points among the mesh vertices to which supports and loads should be applied (Figure 116, 117). One support point is selected at each of the four corners restraining translation in the three dimensions. For shell topologies, wind load is applied on the exterior mesh vertices. For lattices, wind load is applied at the beam nodes. To make sure the resultant of point loads (kN) equals the prescribed wind uniformly distributed load (kN/m$^2$), the influence area of each point load is estimated and the prescribed wind load is multiplied by the area.

For the FEA analysis element geometry, supports, loads, material and cross section properties must be specified and input in the assemble model. These parameters serve as to be input to the solver for first-order structural analysis for small deformations. For lattices, a cylindrical cross section is defined with radius of 1.5 mm while for shells a mesh thickness of 1.5 mm is input. The material properties are directly defined by the initial user input, as for the heat transfer analysis.

The final part of the script is created to retrieve and visualise the results of the analysis (Figure 118). Diagrams for deflection and stress are created using the Shell View and Beam view component. Moreover, the Line-to-Beam component which is used to define lattices as array of lines is able to define whether bending moments arise in the structure. In this way, the stretch or bending dominated behaviour of the different alternatives can be assessed.
Topology Optimisation

For Topology Optimisation Millipede plug-in for Grasshopper (Panagiotis, 2014) was used, which contains a library of fast structural analysis algorithms for linear elastic systems. The TO algorithm uses the SIMP method, making it possible to obtain gray-scale solutions for elemental densities. For the analysis, a model was built simplifying the target design into a simple volume. Supports and loads also need to be modelled as volumes. The intersection of those with the boundary volume represents the space on which they act. This data serves as input to the model builder component. Here, the resolution of the model is set defining the number of finite elements discretising the design geometry, which was set to 20 for a convenient trade-off between speed and detail of results. The FE model is used in the solver for performing the TO, using the SIMP method (Figure 120). The main optimisation parameters are:

- number of iterations for each optimisation step (10);
- smoothing factor which is applied to avoid generation of check patterns (0.8);
- target density, which describes the desired fraction of the overall material after the optimisation;
- penalising factor, which is set to 1 in order to obtain a wide range of material density in the overall distribution as discussed in Section 2.3.2.

The visualisation of the resulting geometry as mesh is done by drawing contours around material elements with same prescribed density. Data resulting from this analysis is a list of density values for each finite element, indicating the percentage of material needed for the given boundary conditions. This list can be visualised as a density map. The same can be done for the list of elemental deflections and Von Mises stresses.

Panel Voxelisation

In order to be able to apply the cell geometry to the façade panel, this volume is discretised into a three-dimensional grid of boxes. Crystallon plug-in includes a pre-defined component for this operation but, in order to speed up the computational process, this was scripted using GhPython. The script is used to define a point cloud with prescribed distance in x, y and z according to the desired cell size. Its output is a list of 3D points which are used as base points to generate voxels as boxes.
Dynamic Relaxation
As form-finding tool, dynamic relaxation is implemented in Kangaroo plug-in for Grasshopper (Piker, 2017), which is used to morph the voxel grid. In order to run the dynamic relaxation solver, a model is set up containing springs, particles and anchor points. The springs correspond to the edges of the boxes resulting from voxelisation, and the particles correspond to the vertices. The anchor points are selected among the particles which lie on the outer surfaces of the façade panel, so that the resulting relaxed geometry is contained within the boundary volume.

Particles are assigned a strength and length value, which are parameters controlling the deformation of the model. Although these values do not correspond to real physical quantities, the length of the springs is used to control the deformation in the model according to the topology optimisation results. First, a list of attractor points is created among the list of centroids of the finite elements, by selecting the elements with highest prescribed density (Figure 123). Then, a custom python script is created which evaluates the distance between the springs’ end points (particles) and the selected attractor points. The output is a list of lengths for each spring: the closer a spring is to the attractor points, the shorter its length, resulting in a smaller voxel size. At the same time, springs are assigned strength values according to their proximity to the attractor points: short springs are assigned higher strength and vice-versa.

In order to have better control over the final geometry, two different types of springs are defined: one including the springs along y and z-axis and one including the springs in x-direction. In this way, it was possible to assign different strength and length multipliers. This is mainly done because of the elongated cell sizes. The deformation of the shortest voxel edges (along x-axis) would cause the final geometry to self-intersect if assigned the same values as the long edges.

The Kangaroo Bouncy solver is used to perform dynamic relaxation. This numerically approximates the model continuous behaviour with discrete time steps to calculate the new position of springs and particles. The threshold value, representing the average moment within the structure, is assigned a very small number as default (1e-15) as default. The number of iterations for each result output is set as 10. After equilibrium in the system is reached, the solution is converged. The output of the model is the list of new particles and springs which represent the new three-dimensional voxel grid.

Geometry morphing
Each voxel defining the façade panel shares at least three sides with the adjacent voxels. Since Kangaroo dynamic relaxation requires each particle to be unique, duplicate points among the voxel vertices are eliminated. However, these points need to be created again in order to describe the final array of morphed voxels to which the cell geometry is applied. To do this, a custom python component was created which retrieves the data structure of the initial voxel vertices list, clarifying which items in the list are duplicated as they represent vertices of different voxels. The same data structure is applied to the list of points (particles) resulting from dynamic relaxation to create the new list of voxel vertices. According to this list of points, the new voxels can be created in Grasshopper as twisted boxes.

Finally, the cell topology is applied to the new voxel grid using the Crystallon components described above. The final geometry is generated as mesh, which is then used as input geometry for the structural validation using Karamba3D for Grasshopper. In order to be exported to .STL format for 3D printing, the mesh is offset to create a closed solid geometry.

Structural Validation
A series of analysis in Karamba3D (Preisinger, 2018) was performed to assess the structural behaviour of the façade panel, comparing the initial geometry and the morphed one. The analysis accepts the mesh generated in the main parametric model as input geometry. The first part of the script retrieves the appropriate points among the mesh vertices to which supports and loads should be applied. Multiple support points are selected at the four corners to approximate the support condition of a façade steel bracket. Wind load is applied on the exterior mesh vertices as point load. To make sure the resultant of point loads (kN) equals the prescribed wind uniformly distributed load (kN/m²), the influence area of each point load is estimated and the prescribed wind load is multiplied by the area. For the FEA analysis element geometry, supports, loads, material and cross section properties must be specified and input in the assemble model. These parameters serve as to be input to the solver for first-order structural analysis for small deformations.

The final part of the script is created to retrieve and visualise the results of the analysis. Diagrams for deflection and stress are created using Shell View component and the deformed structure can be visualised using the Model View component (Figure 126).
For retrieving the maximum deflection, the middle point of the panel is selected and the distance between the point on the initial geometry and the same point on the deformed model is measured. Values of principal stresses and principal stress lines are retrieved in the model using Result vector on shell component. For verification of usability and safety the maximum deflection and principal stresses in tension and compression are compared with the allowable limits.

Adapting the digital workflow to free-form design spaces

Adapting the digital workflow to free-form design spaces requires some adjustments to the script presented above. These mainly concern the strategy adopted to voxelize the design space. In particular, instead of considering the design space as a closed volume to fit the voxels in, the free-form design space is considered as a loft between two surfaces. The voxels are defined according to the network of isolines defining the surfaces so their dimensions depend on the UV parameters and on the assigned thickness value. Both topology optimisation and dynamic relaxation can be performed on free-form geometries without substantial modifications in the workflow. However, further refinement is needed to automate the translation procedure from the morphed grid derived from dynamic relaxation to the morphed voxel array into which the cell topology can be morphed.
5.7 Application of AM envelope in architecture

The architectural application of the envisioned façade component can be proposed according to two main directions. One approach is to consider the element as an infill core geometry for structural and thermal performance to be enclosed between two thin skins. An alternative approach, more radical and true to the premises of this study, is to consider the element as an integrated component in which the outer skins can be designed as a continuous geometry to be produced with additive manufacturing. An additional set of possibilities opens up when considering the design and manufacturing of free-form components which would embed an architectural vision per se.

Infill geometry

As an infill geometry the façade element could provide stiffness and thermal insulation. The resulting component can be considered as a sandwich panel, requiring the assembly of different materials. Compared to traditional architectural components of this kind, such as stud-walls, it would not need any substructure element. An interesting application for an element as such would be a free-form envelope component which is usually difficult to achieve with traditional systems (Figure 128). The sandwich panel could be placed either in between the structural slabs or in front of them. As explained in section 4.2, the chosen support type can be defined within the boundary conditions of the topology optimisation model.

The exterior skin material would determine its performance in terms of visual comfort and aesthetics. Opaque materials could be chosen with the desired finish to enclose the infill geometry. In this case, the cellular geometry of the panel would be hidden and serve only thermal and structural functional requirements. Alternatively, transparent and semi-transparent materials could be used for the exterior skin such as glass or textiles. In combination with the use of transparent filaments for 3D printing, the façade element would result in a translucent envelope component in which the cellular geometry is visible and can contribute to the architectural language.

Indeed, visual comfort is an additional requirement that could be taken into account in the design of the façade component. Considering the porosity of the cellular geometry as a driving factor for light admittance through the façade, the geometry could be generated in such a way to achieve a higher level of porosity in a chosen area. This can be done by assigning a prescribed relative density prior to the topology optimisation process. The resulting optimised geometry would be morphed accordingly to allow for the desired porosity to light (Figure 129).
To move on from the concept of assembly of different materials, the envisioned façade element can be considered as an integral façade component, where the geometry embeds the outer skins of the panel. Also in this case, the use of a transparent filament would allow for the design of a translucent component, controlling the way light gets diffused within the room.

An interesting direction towards this concept is the idea of integrating additional performance within the component. According to the analysis of the different façade requirements, provided in Section 2.2.2, acoustic performance looks promising for integration within the design. Sound absorbing porous materials, such as acoustic foams, can be designed as periodic cellular structures to obtain sound absorption properties as shown by Deshmukh et al. (2019), Figure 131. In case of the proposed design, cell size, porosity and topology could be further explored towards this direction.

Architectural expression is another performance that could be tackled by the façade component. Considering geometrical complexity as the key potential of additive manufacturing, architectural expression could be integrated in the design of a 3D-printed façade element. With the advent of new digital tools for designers, along with implementation of alternative production techniques, the building envelope is facing a revolution in terms of aesthetics, with an increasing tendency to design bespoke envelopes with complex geometries. An interesting examples of this approach is the SFMOMA expansion designed by Snøhetta. The eastern façade of the building features an original form, inspired by sea waves, which is expressed by more than 700 unique FRP panels. These cladding panels are produced using CNC milled EPS foam moulds and are affixed to a unitised curtain-wall system with the help of metal intermediate elements (Figure 132).

For applications as such, an integral, additively manufactured façade component would be an interesting solutions, as it would reduce the need of assembling different materials along with labour intensity for production and tooling costs. Instead of considering the external skin as an additional layer on top of the functional ones, this could be integrated within the element geometry and produced with the same production method in one go (Figure 133).
Towards an AM envelope system

Some relevant aspects regarding the applicability of the designed façade element within the framework of an additively manufactured façade system have only been acknowledged but not really tackled in this study. Further research and investigation are needed to define the façade concept as a marketable envelope component. In particular, crucial aspects regarding detailing and performance of the façade component should be investigated to further define the façade concept. These mainly concern assembly, air and water tightness and fire-safety.

In particular, the assembly in relation to the building structure and the joining of different elements together needs to be addressed. One of the advantages of 3D printing is the possibility to embed and accommodate connection elements within the geometry. This could be done for the fixing element connecting the façade to the building structure, as well as for the connection between different panels. The joining between different modules can be designed using rubber gaskets which are able to ensure air tightness and accommodate the different deformations and expansions as in curtain wall systems. The design of connections and detailing of the elements is also be relevant for achieving water tightness: the outer skin of the element can be designed in such a way that water cannot penetrate through it or, alternatively, drip edges should be designed to allow drainage of water.

Fire safety is another important performance required by the building envelope: façade components should be able to prevent the spread of fire within the building and keep intact for a long enough for safety measures to be taken. Further investigation on the properties of 3D printing filaments is needed to assess whether the chosen material would comply with the fire safety regulations. In general, the fire resistance of 3D printed parts can be achieved by applying coatings to limit flame spread and smoke development within the material. Another approach is using additives which modify the material structure. Flame-retardant additives are commonly added to flammable polymers enhancing heat absorption, creating protective layers on the material at high temperatures and limiting the emission of combustible gases. 3D printing filaments with flame retardant properties already exist in the market. The main disadvantage connected to them is the high melting temperatures which make them difficult to print and not suitable for every kind of printer.

As a final remark, it is important to acknowledge the lack of regulations which specifically deal with 3D printed materials and components so that the use of these techniques in the building industry is still limited to exceptional conditions. The increasing interest for additive manufacturing in the building industry is expected to promote the elaboration of new codes and assessment methods.

References:


This chapter presents the results of the prototyping phase in which different geometry samples were performed in order to investigate how the envisioned envelope component can be produced with Fused Deposition modelling. Preliminary tests were done to gain insight on the different printing settings and to assess the manufacturability of the designed geometry. Finally, a 1:1 prototype of a part of the façade panel was produced using a large-scale industrial FDM machine.
6.1 Additive Manufacturing tests

After the performance of the façade component was validated, the research focused on its manufacturability using Fused Deposition Modelling. This was done using an industrial large-scale 3D printer, the Xcet, produced by Leapfrog, which is available at the Laboratory for Additive Manufacturing at the TU Delft Faculty of Architecture. This 3D printer features a massive build volume (55 x 50 x 250 cm) which allows for full-scale production of large objects. This was equipped with a 1.2 mm nozzle extruder and fed with PETG filament. The printer settings were controlled using the slicing software Simplify 3D. Preliminary experiments were done by printing regular sample geometries as well as parts of the panel geometry. These were aimed at defining the most suitable printing settings for the production of the prototype with the following objectives:

- Minimise printing time
- Minimise material wastage
- Maximise print quality (sticking to bed, oozing)

Minimise printing time

As observed in Section 4.4, speed of extrusion and printing quality are closely related. A good compromise should be found between speed and accuracy. According to the different tests that were performed, the maximum achievable extrusion speed is 40 mm/s. However, this extrusion speed proves only effective when continuous nozzle paths are considered. In regard to the panel geometry, this means that higher speeds are achievable during the printing but a lower speed should be kept for the first layers where the path of the nozzle is not yet continuous. An additional strategy to minimise printing time is adjusting the ratio between layer height and layer width. In case of the specific design, for thermal insulation reasons the geometry needs to be printed as a single shell so that the layer width corresponds to the effective thickness of the walls. Layer width depends on thickness of the nozzle (1.2 mm) and influences the strength of the printed geometry. Large layer width allows for maximising contact area between layers and improving adhesion (Figure 135).

Layer height depends on layer width as well and is a main factor reducing or increasing printing time. Resolution in the vertical direction increases with lower layer height, and so does printing time (Figure 136). For this large scale 3D printing, layer height is to be maximized to decrease the overall number of layers. As a general rule for achieving good printing quality, layer height should be kept between ¼ and ½ of the layer width. The following relation is often used: layer height = layer width – nozzle thickness.

In order to test the effect of layer height settings, a simple rectangular geometry was printed with different layer height, 0.4, 0.6 and 0.7 with a layer width of 1.7 mm. The results of the print are shown in Appendix B. An additional printing test was done with a layer height of 0.8 mm. However, in this case poor adhesion between layers made the printing fail. An optimal combination between layer height and width was found to be 0.7 and 1.7 mm respectively.

Minimise material wastage

Minimal material wastage is a natural feature of additive manufacturing production techniques. However, this is only true when geometries are designed for it. The suitability of the chosen geometry for 3D printing was tested during the printing of the samples presented in section 4.4. Then, shell geometries were found to be well printable with traditional FDM technique while for lattices an alternative production technique was suggested.

In regard to the final façade design, the chosen geometry can be printed without any support structure. Although the geometry is characterised by holes, the intertwined nature of the cell ensures that bridging parts of are properly supported and overhangs are never too steep. Moreover, high speed for the extruder cooling fan ensures that overhanging parts retain their position after extrusion. Critical part of the geometry are the unconnected edges, which in a single cell configuration cannot be perfectly printed. These edges, however, are actually connected in the panel design so that too wide overhangs are avoided. Although the geometry is printed with a single shell thickness, infill structure is not needed thanks to the intertwining surfaces which provide stiffness in all three directions (Figure 137).
extruded when the extruder moves around the building platform (Figure 138). For overcoming this, retraction settings had to be tweaked. In particular, retraction speed was increased, resulting in a quick retraction of the filament after a completed path extrusion. Additionally, retraction distance, designating the length of the filament is pulled out from the nozzle, was increased.

Overall, temperature is a very important parameter influencing the quality of the print. Both nozzle and heated bed are required to have a certain temperature to ensure proper adhesion and extrusion of the material. 3D printing filaments come with a technical data sheet prescribing the range of temperatures which can give optimal results in terms of printing quality. The most suitable temperatures for the specific printing machine were identified by tweaking the values in order to achieve constant, good quality extrusion with no imperfection within the filament.

6.2 Prototyping

Information retrieved during the printing tests served as guideline for printing a prototype: the different settings described above were used to generate the machine g-code. Ideally, the façade component could be printed in one go using a large industrial printer. On the one hand, this would make the production process completely automated and minimise labour related to the assembly. On the other, it would result in higher risks of inaccuracies and failure of the print.

Considering the capabilities of the FDM printer available at TU Delft Faculty of Architecture, the full façade panel could be produced in different parts. The size of the modules can be chosen taking into account achievable printing volume in relation to printing time (Figure 137). When defining the different modules, careful attention needs to be paid in the slicing the geometry in order to avoid generation of discontinuous surfaces hindering a successful printing.

The modules could then be glued using different methods. The main alternatives are compared in Table 33. All in all, considering surface quality, ease of application and cost, Superglue appears to be the best alternative for bonding different parts.

<table>
<thead>
<tr>
<th>Material</th>
<th>Technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superglue</td>
<td>adhesive bonding</td>
<td>strong bond, invisible seams</td>
<td>extremely fast curing</td>
</tr>
<tr>
<td>Acetone</td>
<td>welding</td>
<td>strong bond, invisible seams</td>
<td>risk of damaging thin 3D printed parts by dissolving the filament</td>
</tr>
<tr>
<td>Hot glue</td>
<td>adhesive bonding</td>
<td>fast drying</td>
<td>thick seam between parts</td>
</tr>
<tr>
<td>Epoxy</td>
<td>adhesive bonding</td>
<td>strong bond, can also be used as filler</td>
<td>requires time to apply on parts (mixing resin and hardener)</td>
</tr>
</tbody>
</table>

Table 33: Comparison of different bonding methods
To the scope of this study, the prototyping phase aimed at demonstrating the fact that the element geometry can be successfully printed in 1:1 scale. The production of the full element has proven to be unfeasible due to several practical limitations related to the available facilities:

- the build volume of the FDM printer is not big enough to accommodate the whole width of the façade component;
- the use of the printer was limited to regular university opening hours, resulting in the need of interrupting the printing everyday.

Taking into account these aspects, the final product for the prototyping phase was a small part of the element, which was considered exemplary of the way the cell topology is morphed within the façade element. In order to make the production possible, this part was produced in different modules which could be printed within 6 hours and were then assembled together using superglue (Figure 140).

The printing of the geometry proved to be successful, especially for all those areas in which the tool path is continuous. However, the quality of the print greatly worsens at the unconnected edges of the surfaces, whose occurrence increases in the prototype, compared to the entire panel, due to the slicing of the geometry. In general, in relation to the quality of the printed part, some key facts have to be taken into account:

- In order to minimise the printing time, a high layer height was chosen resulting in a lower resolution;
- In order to allow for high layer heights, a significant layer width was chosen. This resulted in lower resolution for the print in the horizontal plane. Moreover, this meant that a large amount of material had to be processed in the hot end and, consequently, the extruder temperature was never really able to maintain the optimal value;
- the machine was not equipped with a heated chamber, resulting in non optimal cooling of the layers;

Overall, the geometry was designed to be printed at full scale or in very large parts. Therefore, significant improvements on printing quality are expected in case facilities allowing the envisioned production technique are used.

References:


CHAPTER 07 - CONCLUSION

This chapter presents the main findings of this study by answering the research questions presented in the methodology section. In the discussion, the limitations of the research are stated and directions for future related research are presented.
7.1 Answering research questions

To conclude the study, the research questions addressed in the research were answered, starting from the subquestions and addressing the main question as last.

What is geometrical and material complexity? How can the thermal and mechanical properties of complex geometries be assessed?

Geometrical and material complexity is found in spatially varying structures where form and material properties change to respond to functional requirements. The properties of such structures, called cellular solids, depend on the material they are made of, the topology of the cell and its porosity. Thermal and mechanical properties of these structures can be assessed in a first approximation by distinguishing among two main groups: strut-base geometries (lattices) and surface-based geometries (shells). Analytical models have been proposed for calculating the effective thermal conductivity, Young’s modulus and strength of this geometry. However, these do not take into account the influence of specific topology and are not able to give insight on the radiative and conductive heat transfer modes. FE analysis is the most suitable tool for studying the performance of such complex geometries, along with physical tests.

Which materials, among the ones that can be used in AM, are most suitable for producing an envelope component for thermal insulation and structural stiffness?

Polymers are the most promising materials for the purpose of this design due to their excellent thermal properties. AM polymers are characterised by similar values of thermal conductivity while their strength and Young’s modulus can vary significantly. Compared to the other materials for additive manufacturing like metals and ceramics, polymers are much more cost-effective, which makes them suitable for use in the building industry. Polymers with advanced mechanical properties, however, can result in higher costs.

How can a façade component be processed with AM? What are the different production techniques and their limitations related to the complex geometries?

Large scale additive manufacturing for the built environment has already been proven to be feasible using extrusion-based techniques for concrete mixtures and polymers. Fused Deposition Modelling is a relatively low-cost and high-speed process, which makes it suitable for the production of façade components. In relation to complex geometries, printing tests on samples have shown that traditional FDM technique is applicable for production of shell geometries and that the production time and quality can greatly improve depending on the continuity of the nozzle path. On the contrary, horizontal slicing is not suitable for lattices as the struts require support materials to be printed. Multiplane strut-by-strut extrusion is the best production technique to produce lattice geometries. This requires the use of extruder coupled with a robotic arm and a powerful cooling fan which allows the struts to retain their position after extrusion.

What strategies can be adopted to design complex geometries tackling structural and thermal performance in a façade component?

Based on the literature study, two strategies have been proposed to design the façade element: working at the component scale and at the material meso-scale. On the one hand, structural performance is preeminent when considering the design space of the entire component, as load transfer in the material results in different structural behaviours and requirements at different parts of the panel. Thermal performance, on the other hand, is influenced by the meso-structure of the material, irrespectively of the position within the component boundary. The meso-structure of the material also influences the overall structural properties of the panel. Therefore, a geometry exploration was carried out at the scale of the material unit, combining thermal and structural aspects, and a second geometry exploration was done at the scale of the component according to structural principles. The outcomes of these two parallel processes were then combined to create a spatially varying structure within the panel.

What is the optimal geometry for the component to achieve structural stiffness? Which tools or procedures are best suited to design it?

Finding the optimal geometry for achieving a given structural performance can be addressed using topology optimisation, which consists of iterative improvement of material distribution, given a design space. In relation to AM and complex geometries, the use of an unpenalised SIMP method for topology optimisation was explored as it allows for a solution with a wide range of prescribed densities which can be produced using additive manufacturing techniques.

At the material meso-scale, structural behaviour of complex geometries can be designated as stretch-dominated or bending-dominated. Lattice structures are most efficient in structural performance as their geometry allows them to transfer loads only by means of tension and compression. Through the FE simulations, it was found that only perfectly triangulated lattices exhibit a perfectly stretch-dominated behaviour while in other geometries bending stresses arise. Due to bending, shell structures are generally less efficient in structural behaviour but their higher relative density makes them comparable to lattices. However, it should be noted that for shell geometries failure by buckling can cause failure at lower stress levels.

What is the optimal geometry for the component to achieve thermal insulation? Which tools or procedures are best suited to design it?

Good insulation properties of cellular geometries result from the low thermal conductivity of air, composing the gaseous phase. Therefore, porosity is beneficial for decreasing thermal conductivity. However, heat transfer in cellular geometries also depends on convection and radiation. To minimise convection, air cavities should be kept within small widths and, therefore, elongated cells with small dimension in the direction of heat transfer were designed. Radiation accounts for a large part of the global heat transfer and shell geometries benefit from the shielding properties of the surfaces composing the cell. According to the results of the FE simulations, lattice structures were found to be more efficient than shells in the thermal insulation, mainly due to their higher porosity.

How can digital tools aid the design of the proposed façade component?

The design of complex geometries was done using parametric tools. This allowed for quick modelling of design alternatives and for performance-driven geometry generation. Digital tools were also used to assess the structural and thermal performance of the different alternatives, using finite element methods as the complexity of the geometries being studied prevented relying on analytical models. Digital tools made it possible to make informed design decisions and verify the effectiveness of the proposed strategies.

The study of thermal performance required heavy computation processes which had to be fine-tuned in order to be used as a tool to inform the design along the process. To speed up the computation process, the effects of convection and radiation had to be estimated rather than calculated. To this purpose, the model was simplified and its validity was verified by comparing the results with the outcomes of the physical tests. As regards the structural performance, digital tools could be used within the parametric design environment both for topology optimisation and for structural analysis. This was particularly advantageous when using the numerical and geometrical outcomes of topology optimisation as input for the design and assessing the relation between geometry and structural behaviour. Although more
As an outcome of this study a computational workflow was defined for designing envelope components with complex geometries for thermal and structural performance. The script can be used as a design tool through which the form of envelope components can be generated, according to loads acting on the façade and desired cell geometry.

How can the optimal geometries be developed to create the proposed façade component?

According to the results of the geometry exploration at meso-scale structural and thermal performance indicators point towards different geometry alternatives. Among the different options, the best performing geometry for structural performance is never the best choice for thermal performance and vice-versa. However, geometries with overall good behaviour were identified and selected for further exploration in the design. All in all, lattices and shells resulted to have comparable performances but high porosity of lattice structures makes them more interesting in the perspective of weight reduction. The choice of one geometry type over the other was tightly related to manufacturing aspects. The final form was generated using a shell cell type to be able to test the additive manufacturing process using the FDM printer available at the TU Delft Faculty of Architecture. Nevertheless, the strategy for combining the results of the two geometry explorations was elaborated considering both geometry types and pointing out the best alternative considering the specific production technique.

Overlapping the results of geometry exploration at meso-scale and those of topology optimisation was made possible by the use of digital tools. Due to the high number of elements involved, these processes resulted in heavy computations, suggesting that further refinement is needed to achieve higher efficiency. The soundness of the strategy chosen for the final design was validated by the structural analysis performed on the façade panel.

How can the potentials of AM be used to create a multi-functional façade panel with complex geometries for optimal thermal insulation and structural stiffness, making efficient use of the material?

This study aimed at investigating how structural and thermal performances can be addressed using complex geometries and integrated into a mono-material façade panel produced by additive manufacturing. The research focused on exploring the relation between geometry and performance at different design scales, taking advantage of the capabilities of additive manufacturing to design non-standard spatially varying geometries. The results of the study showed that thermal and structural performance have divergent implications on geometry and that, in order to tackle both aspects together, compromises on optimality have to be made.

To comply with the chosen target performances, the amount of material used in the final design is mainly driven by thermal principles while the distribution of the material within the panel results from structural concerns. The use of topology optimisation related to material use would become more crucial if a smaller amount of material was involved and the component was to work closer to its material structural limits. Improving thermal resistance is a point to be further explored not only in relation to geometry but also to material properties.

Although it was not possible to produce a full-scale prototype as envisioned in the methodology, the feasibility of the production was demonstrated through different production tests. These showed that the designed geometry is suitable for additive manufacturing. However, production time is a major limitation of the process; improving production efficiency is still required to scale up from prototype to building component.

This study has explored different strategies for the integration of thermal and structural aspects using complex geometries to distribute material according to the required performance. The final design shows how such strategies can be implemented to create a mono-material façade component where the same element serves multiple functions without the need for additional elements, complying with current regulations for façades. The designed component embodies an alternative approach to the design of the building envelope, moving away from the need to design for disassembly and opening up new possibilities in terms of positive end of life options.

Applying additive manufacturing for the building envelope suggests a set of new possibilities for designers also in terms of aesthetic quality. If geometry and assembly limitations derived from traditional production techniques are no longer there, the building envelope can be conceived as an integrated object in which the shape responds to specific performances and design requirements locally, becoming a mass-customised object. In this scenario, performance can be the driving force for the establishment of a new architectural language where engineering and design are inherently related and the shape is an informed geometry embedding material properties, performance and functionality.

Figure 142: Main findings of the study
7.2 Directions for future research

During the development of this study, a number of potential research directions were identified, which would further explore the different aspects involved in this study.

Digital Design

- The proposed workflow for the generation of the geometry for the façade could be further refined to become a complete parametric design tool that architects and engineers could use. The tool could also include parameters related to the additive manufacturing process.

- The problem of finding a suitable geometry for different performance could be approached from an optimisation standpoint. The geometrical variables influencing the thermal and structural performance at the cell scale could be transformed into parameters for a multi-objective optimisation process where new cell topologies are created.

Additive Manufacturing

- The implications of the additive manufacturing process in the geometry could be further explored to inform the design of the façade. The objective of the study could be the reduction of printing time towards a more efficient production process.

- Multi-plane extrusion coupled with a robotic arm could be explored as a production technique for components based on lattice geometries.

Performance

- Since thermal performance was found to be crucial in determining the amount of material needed for the façade component, research towards further improvement of the thermal insulation could be carried out. Beside exploring additional geometry options, the material properties could be a direction of research. Polymers with extremely low thermal conductivity and emissivity could achieve lower thermal conductivity values. Additionally, the thermal conductivity of the gaseous component could be decreased if air is substituted with a noble gas such as argon and krypton.

Façade Design

- The concept of AM envelope could be further explored towards the integration of multiple functions such as acoustic insulation and visual comfort, all in one component. The idea of an additively manufactured façade system and its potential applications in the built environment could be a direction of research.

- Crucial aspects regarding detailing and performance of the façade component could be investigated to further define the façade concept such as assembly in relation to the building structure, air and water tightness and fire-safety.

Figure 143: Directions for future research considering the different aspects involved in the study.
**APPENDIX A - Material Properties of 3D printing filament**

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**Technical Data Sheet**

**EPR InnoPET by Innofil3D BV**

Filament suitable for all commercially available leading brands 3D FDM/FFF printers

### Identification of the Material

**Trade name**: EPR InnoPET  
**Chemical name**: MonoPET Polyethylene Terephthalate  
**Chemical family**: Amorphous Thermoplastic Polyester  
**Use**: 3D-Printing  
**Origin**: Innofil3D BV

### Guideline for Print Settings

- **Nozzle temperature**: 220 ± 10 °C  
- **Bed temperature**: Approx. 75 °C  
- **Bed modification**: Tape or glue below 60 °C  
- **Active cooling fan**: YES, 100%  
- **Layer height**: 0.08 - 0.2 mm  
- **Shell thickness**: 0.4 - 0.8 mm  
- **Print speed**: 40 - 80 mm/s  

Settings are based on a 0.4 mm nozzle

### Material Properties

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<td>Density</td>
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<td>Odor</td>
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<tr>
<td>Solubility</td>
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### Mechanical Properties - Tensile Test

- All test specimens were printed using an Ultimaker 2+ under the following conditions:  
  - Printing temperature: 210 °C  
  - Heated bed temperature: 75 °C  
  - Print speed: 40 mm/s  
  - Number of shells: 2  
  - Infill under 45°

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<th>100%</th>
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<tr>
<td>Tensile strength (MPa)</td>
<td>11.1 ± 2.2</td>
<td>22.8 ± 4.9</td>
<td>27.7 ± 1.4</td>
<td>40.9 ± 1.9</td>
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<tr>
<td>Force at break (MPa)</td>
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<td>22.7 ± 4.9</td>
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<td>Elongation at max force (%)</td>
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<td>3.0 ± 0.2</td>
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<tr>
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<td>Elongation (%)</td>
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### Mechanical Properties - Impact Test

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  - Printing temperature: 210 °C  
  - Heated bed temperature: 75 °C  
  - Print speed: 40 mm/s  
  - Number of shells: 2  
  - Infill under 45°

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<td>Charpy (ep)</td>
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Preparation date: 08-06-2016  
Version No.: 2.0
### MECHANICAL PROPERTIES | FLEXURAL TEST

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<th>Max. roundness deviation 2.85</th>
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### LIST OF COLORS AND CERTIFICATIONS

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* This overview is generated using information obtained from the raw material suppliers.
** RAL number used to manufacture the (semi-)transparent colour.

### Certifications/approvals

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APPENDIX B - 3D printing tests with Fused Deposition Modelling

Sample for physical test - Gyroid geometry

Sample for physical test - Diamond geometry

Sample for physical test - Schwartz's P geometry

Lattice geometry printed along x-axis

Lattice geometry printed along z-axis

3D Printing on LeapFrog Desktop printer
Leapfrog Xcel printer

Printing of façade panel sample

Façade panel sample geometry

Printed geometry detaching from the heated bed

Gyroid cell geometry - detail of oozing issue

Gyroid cell geometry - full scale sample
**APPENDIX C - Heat Flux Physical Testing**

- **temperature sensor**: $T_e$
- **heat flux plate**
- **data logger**

**Heat transfer testing set-up**

3D printed array - Gyroid cell

3D printed array - Diamond cell

3D printed array - Schwartz's P cell
### Gyroid cell - Measurement 1

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### Schwartz's P- Measurement 2

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### Diamond cell - Measurement 2

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1. CONDUCTION IN SHELL AND LATTICE GEOMETRIES

- FC Cubic
- Gyroid

2. CONDUCTION IN SHELL AND LATTICE STRUCTURES COMPARING DIFFERENT CELL TOPOLOGIES

- BC Star
- BC Cubic
- FC Cubic

- Star Tetrahedron
- Vertex Octahedron
- Tetrahedral

3. CONDUCTION AND CONVECTION

- Gyroid
- Diamond
- BC Cubic

4. CONDUCTION IN SHELL AND LATTICE GEOMETRIES WITH PETG SHEETS

- BC Star
- BC Cubic
- FC Cubic

- Star Tetrahedron
- Vertex Octahedron
- Tetrahedral
5. CONDUCTION AND RADIATION IN SHELL AND LATTICE GEOMETRIES WITH PETG SHEETS

6. CONDUCTION WITH PETG SHEETS WITH AN ADJUSTED AIR THERMAL CONDUCTIVITY

7. COMPARING PERFORMANCE OF DIFFERENT CELL SIZES
7. COMPARING PERFORMANCE OF DIFFERENT CELL ARRAYS

APPENDIX E - Structural Analysis in Karamba3D-Grasshopper

15 x 15 x 3.4 cell size

Deflection in regular panel - max. 3 mm

Deflection in morphed panel - max. 3 mm

First principal stress in regular panel

Second principal stress in regular panel

First principal stress in morphed panel

Second principal stress in morphed panel
25 x 25 x 3.4 cell size

Deflection in regular panel - max. 6 mm

Deflection in morphed panel - max. 3 mm

First principal stress in regular panel

Second principal stress in regular panel

First principal stress in morphed panel

Second principal stress in morphed panel