**Graduation Plan: All tracks**

Submit your Graduation Plan to the Board of Examiners (Examencommissie-BK@tudelft.nl), Mentors and Delegate of the Board of Examiners one week before P2 at the latest.

The graduation plan consists of at least the following data/segments:

<table>
<thead>
<tr>
<th><strong>Personal information</strong></th>
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<tbody>
<tr>
<td>Name</td>
<td>Valeria Piccioni</td>
</tr>
<tr>
<td>Student number</td>
<td>4728637</td>
</tr>
<tr>
<td>Telephone number</td>
<td>+393331331445</td>
</tr>
<tr>
<td>Private e-mail address</td>
<td><a href="mailto:valeria1.piccioni@gmail.com">valeria1.piccioni@gmail.com</a></td>
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<th><strong>Studio</strong></th>
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<tbody>
<tr>
<td>Name / Theme</td>
<td>Building Technology Sustainable Design Graduation Studio</td>
</tr>
<tr>
<td>Teachers / tutors</td>
<td>Dr. Michela Turrin, Dr. Martin Tenpierik</td>
</tr>
<tr>
<td>Arguementation of choice of the studio</td>
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<th><strong>Graduation project</strong></th>
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<tr>
<td>Title of the graduation project</td>
<td>Developing a mono-material, multi-functional façade panel with complex geometries for structural and thermal performance produced by additive manufacturing</td>
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<th><strong>Goal</strong></th>
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<td>Location:</td>
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<tr>
<td>The posed problem,</td>
<td>Buildings and construction industry together account for 36% of global final energy consumption and 39% of energy-related carbon dioxide (CO2) emissions [1]. Additionally, based on volume, construction and demolition waste is the largest waste stream in the EU, representing about one third of all waste produced [2]. Growing concern about resource and energy consumption has brought new challenges for design of buildings.</td>
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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 \[3\]. 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.

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 monomaterial components, integrating different functions;

- Waste material is reduced as a direct consequence of the additive manufacturing process;

Therefore, AM has the potential for creating monomaterial multifunctional façade components with
complex geometries to achieve specific performances, without having to rely on the assembly of different layers.

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 multi-functional façade panel with complex geometries at meso-scale for climate control (component scale);

- the design of topologically optimised structural connections for load transfer (node scale);

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.

research questions and results

Main research question:

• 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?

Sub-questions:

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

• Which materials are most suitable for achieving thermal insulation and structural stiffness?

• How can the material and the geometry be processed with AM? What are the different production techniques and their limitations?

• 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?

• How can these optimal geometries be


developed to create a façade panel?

design assignment in which these result.
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.

Process
Method description

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 to be achieved
3. 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 in order 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. *IntraLattice* is a Grasshopper plug-in that will be used to generate solid lattice structures within a design space.

The assessment of the designs will be done by means of physical testing and digital tools. In particular:

a) 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 *Millipede* and *tOpos* will be used. In the preliminary design phase a benchmarking among these tools on speed, robustness, functionality and flexibility will be done to evaluate the best option.

b) Samples will be produced using AM techniques. In this context some important aspects will be explored:

   i. Dimensional accuracy and tolerances
   ii. Handling of the geometry and information transfer
   iii. Slicing of the geometry
   iv. Need for infill/support structure
   v. Printing time
   vi. Surface quality

c) 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 optmised geometry will be designed with focus on:

   d) Geometry and material distribution within the panel  
   e) Assembly and relation to building structure  
   f) Integration with other building components (thermal mass, openings)  
   g) Façade system

The new concept will be assessed in terms of environmental impact (embodied energy, CO₂ emissions, EoL potentials) and compared to a tradition façade component with similar performance.

5. PROTOTYPING
A prototype will be built to test the feasibility of the production by AM and verify the assumptions on the required performances. Results from the production of the samples for testing in phase 3 will be taken into account.

Research Structure
Research Workflow Overview

1. FOUNDATION KNOWLEDGE
   - Geometrical Complexity
     - cellular solids
     - thermal performance
     - structural performance
   - Additive Manufacturing
     - workflow
     - scale
     - material
     - techniques
   - Structural performance and geometry (TP)
     - definition
     - methods
     - TO and rev
   - Thermal performance and geometry
     - tools
     - geometry
     - insulation
     - materials

2. DESIGN BOUNDARIES
   - Material
     - Process
     - Component Scale
   - Geometries to explore

3. DESIGN EXPLORATION
   - Digital Tools
     - Geometry Modeling
     - Model Setup
     - Topology Optimization
     - Simulation (Structural)
     - Simulation (Thermal)
   - Sample Production
     - tolerances
     - printing time
     - cooling
     - infill
     - support
     - surface quality
   - Physical Testing
     - experiment setup
     - heat flow measurements
     - verification

4. COMPONENT DESIGN
   - Selection between geometries within the panel
   - Assembly options: Relation to structure
   - Facade system
   - Environmental impact assessment

5. PROTOTYPING
   - production
   - feasibility assessment
   - performance verification

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

Which materials are most suitable for achieving thermal insulation and structural stiffness?

How can the material and the geometry be processed with AM? What are the different production techniques and their limitations?

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?

How can these optimal geometries be developed to create an integrated facade panel?
**Literature and general practical preference**

**REFERENCES**


WEBSITES

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


Reflection
Relevance

SOCIETAL

Energy and resource consumption is now a major concern in the building sector. As governments and international bodies are proposing and adopting measures to face this problem, buildings and particularly façades need to meet challenging requirements in terms of sustainability. Making use of new production techniques such as AM and digital tools, architects and engineers can design innovative building components with low environmental impact. This research aims at contributing to this field by exploring the potential of AM for façade design.

SCIENTIFIC

Ongoing research on the application of additive manufacturing for the building industry show promising results and suggest new ways to regard building components. The
potential applications for the building envelope are still to be investigated. This thesis challenges the traditional concept of façade as array of functional layers and explores how digital tools and AM techniques can be used to create optimised geometries for efficient multi-functional components. A relevant part of the research will be focused on investigating the relation between thermal and structural properties and geometry at meso-scale, thus contributing to a path of research which has been explored in different fields but is relatively new to the built environment.

## Time planning

<table>
<thead>
<tr>
<th>TIME PLANNING</th>
<th>FOUNDATION KNOWLEDGE</th>
<th>DESIGN BOUNDARIES</th>
<th>DESIGN EXPLOSIONATION</th>
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