Graduation Plan

Master of Science Architecture, Urbanism & Building Sciences

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:

Personal information	
Name	Samanwita Ghosh
Student number	5577640

Studio		
Name / Theme	Building Technology / Façade Design + Sustainable Design Graduation Studio	
Main mentor	Dr. Olga Ioannou	Building Product Innovation
Second mentor	Dr. Mauro Overend	Structural Design & Mechanics
Argumentation of choice of the studio	My motivation lies in material-based design and research exploration that reform current façade practices. My professors can guide my interest in novel bio-based materials for innovation with structural applications & systems thinking. The results that this thesis can produce offer a possibility to potentially accelerate the transition to a circular built environment.	

Graduation project	
Title of the Graduation Project	Circular Product Development using Bio-composites in Façade Cladding Systems with Complex Geometry
Goal	
Location	The Netherlands
The Posed Problem	Industrial processes have their own rules & limitations as they rarely fit highly irregular geometry featuring in contemporary complex facades (Lee & Kim, 2012). Articulating these desired geometries and identifying a compatible strategy for production is far from being a linear & deductive process (Vaudeville et al., 2013). The overall energy & project resources spent ranges from minimum for flat straight, singly bent, to the maximum for doubly bent & freeform geometries, eventually depending on the surface typology of the facade panels ordered acc. to structural considerations (Lee & Kim, 2012). If panels are ordered into planar or one-way bent geometries, also briefly called 'developables', the available tooling & machinery make it economical. Developability is a quality of a material to be bent along a single curve geometry and unrolled back into a plane 2D sheet without distortion/creasing after tooling (Duncan & Duncan, 1982).

	With **rationalised facades**, literature proves that even the most **complex forms** can be achieved **through developables**, without the need for exhaustive methods or moulds (Pottmann, et al., 2008). The pairing of economical sheet material with attributes of cost-effective and accessible tooling, or 'developability', makes metal a widely favoured choice for cladding complex facade geometries (Kolarevic, 2001) (Duncan & Duncan, 1982). Through time, sheet metals have been developed to qualify all parameters for facade cladding and available machinery of sheet forming (e.g., stretch bending/roll forming) has increasingly been optimised to exploit the plastic deformation offered by metals. Thus, the sheet-forming industry is more suited to metals, **due to the lack of a material** that is equally **versatile** and fracture resistant. The domain - interdependencies of **geometric complexity**, **technical materials** and **production possibilities** give way to **metals** being **widely chosen** for complex facade geometries due to their **developability**, thus inducing the use of fossil-fuel-based materials in the facade construction sector. Today, with climate vulnerability, depleting fossil fuels, increasing landfills and rapid rise in global emissions, there is a critical need for the next generation of sustainable alternatives for building materials (IEA, 2022). The present literature confirms a plausible opportunity through **biocomposites**, that for specific applications, natural fibres with bioplastics demonstrate **competitive** performances compared to the **synthetic** fibre-matrix composites like non-recyclable **GFRP** (Merhi, 2021). These bio-composites, first developed in 1908 with lignocellulosic fibers and plastics, combine reinforcement and matrix from natural or biobased origins. Biocomposites present a renewable and biodegradable alternative to the fossil fuel-based materials like Aluminium and GFRP increasingly used for complex facade cladding (Shanmugam et al., 2021). **Main Problem Statement** Complex geometries using developable surfaces on Natural Fibre composites have not been reported in literature or practice, hence the desired property of developability in bio composites and an enhanced use of novel bio constituents with closed loop resource flows is underexplored.
Research Questions	The focus of this research is to contribute towards the innovation of fibre reinforced biocomposites and divert from fossil-fuel-based materials like aluminium to biobased constituents. The main goal is to explore the circularity potential and experimentally validate its ease of developability and discover consequent properties of bio composites applicable to façade cladding systems.

	Main Research Question is formulated as: How to engineer a fibre-reinforced biocomposite as a circular alternative to a developable aluminium cladding panel used in complex facade geometry? **Sub-Questions** according to various themes are: *Geometry Analysis in Façade Cladding* Q1. What are complex geometries in relation to facade cladding systems? Q2. What are the opportunities & challenges of circularity in current cladding systems with complex geometries? *Case Study & Material Study* Q1. What are the attributes of state-of-the-art aluminium cladding with developable geometries? Q2. What properties of natural fibre-reinforced biocomposites are applicable to facade cladding systems? Q3. What are the engineering standards and limits involved in fabricating developables of fiber reinforced biocomposite using sheet metal forming? *Production & Prototyping for Circularity* Q1. What is(are) the effective method(s) of production for shaping biocomposites into a developable panel? Q2. What are the differences seen in material, manufacturing, and component scales between biocomposite & aluminium panels for a desired geometry?
Design Assignment	"The concept of developable surfaces has not been implemented for fibrous composites." (Chanda & Bhattacharyya, 2022). If the 'developability' of biocomposites is proven, circularity can be achieved through the facade component on multiple domains. The ability to be formed & reshaped back into a flat sheet without distortion, shall encourage reusability & repurpose potential to maintain the embodied energy at its highest value, throughout its multiple useful lives. Materials from biobased origins shall reduce the carbon footprint at every stage of the lifecycle while minimising waste through circular production methods.

The research-by-design approach will be an experimental and tectonic design exercise.
There are two key quests, the potential of biocomposites to be a circular alternative as a cladding panel and the material behaviour of biocomposites for developing complex geometry.

The research intent is to find suitable fibre architecture and matrix compositions of bio composites and the possibility to be formed into panels using current sheet metal forming techniques for researching its potential of scalability in existing infrastructure.
If the biocomposite can be plastically deformed using existing and optimised fabrication techniques, certain properties desired from metals will be achieved while retaining the flexibility in properties desired from composites that can be engineered for specific facade requirements.

However, **if found** that **the existing methods** used for the case study are **not a suitable technique** to form the bio composites, the technical findings of the first query will inform the ongoing search. The most circular material-manufacturing-design iteration will be researched for Bio composites to be effectively sheet-formed into developable facade cladding panels, without molds and repetitive layup casting, the disadvantage generally associated with (bio)composites.

Expected Outcomes

Empirically proving/validating the developability of Fibrous Biocomposites through Sheet Metal Forming or through modifying Composite Sheet Forming, will **pioneer innovation** for Engineered Biocomposites to parallel with the **reuse potential**, **formability**, and **competence** of metals like Aluminium, with flexibility in constituent engineering & solving the **reusability bottleneck** of fibre reinforced composites like GFRC.

This research gap if addressed can reduce resistance for stakeholders to switch to biobased composites and can lead us to our desired geometries through existing infrastructure without the nature altering consequences of emitting high GHG emissions, generating technical waste streams, or widening resource loops.

Process

Method Description

The research for a circular and developable biocomposite panel will be in six phases with overlapping results and iterations along the process.

Phase 1: Literature Review and Theoretical Framework

The focus lies in extracting necessary information through existing research and available literature related to the chosen topic. This forms the basis for the development of the research framework. Scientific papers, academic journals and books will be consulted for this phase.
Phase 1 will also be a partially ongoing phase, as existing literature will be referred at various stages of the study.
Research objectives here are –

- Study the parameters of complexity in surface geometry and its typology as in current facade cladding systems.
- Compare & contrast the conventional materials across the typology of complex geometry and research the circularity status quo in cladding systems with the existing methods of production.
- Find the opportunities & challenges of circularity in current cladding systems.

Phase 2: Case Study Analysis (Aluminium Cladding Panel)

A façade of the Hoog Catharine, Utrecht (2018) is selected as the case study and analyzed to provide a realistic scenario in defining structural, visual, and assembly criteria of the façade cladding system with developable geometry. Aldowa B.V. and other stakeholders will be contacted for detailed investigation.

Research objectives for Phase 2 is –

- Review an aluminium clad façade with developable geometry as a design case study for insight into the material attributes, component design and method of shaping the facade cladding.

Phase 3: Material Study & Limit Evaluation (Fibre Reinforced Bio Composite)

The focus of this phase is two parts. To evaluate the material, suitable fiber architecture and matrix compositions will be studied and forwarded upon based on previous findings for applicability to facade cladding, and further regarding the geometry of case panel.

Second focus is to investigate the compatibility and limits of shaping methods (from the case study) based on various parameters, by simulations, numerical calculations and (if permitted) experimental methods.

Research objective for Phase 3 would be –

- Examine the structural properties and predict the engineering standard and limits of bio composites with existing production techniques in relation to an Aluminium panel.
- Use simulations to understand material behaviour with existing metal shaping machinery (case study), correlate with limits of bio-composites.

Phase 4: Prototyping & Production Design

In terms of technical findings from Phase 3 for capability with SMF techniques, there would be 2 investigations at Phase 4. Based on technical findings, the final concept for the set up will be formed.

If, the existing SMF methods the case study is ineffective to form developable surfaces with bio composites, then technical findings of the Phase 3 will refine the material and guide in developing a new and suitable method of composite sheet forming.

Research objective for Phase 4 would be –

- Test, if possible, and prototype the developability of the engineered biocomposite with similar fabrication processes as the case study panel.
- Design a circular and suitable method of sheet-forming or shaping the biocomposite as a developable geometry, along with material-based design iterations.

Phase 5: System Refinement & Comparative Analysis

This phase is important for Material Design Iterations. The goal is to keep the geometry constant and iteratively experiment with the panel layout, size, weight, cross sections and physical properties, compositions, and qualities to evaluate the limits of bio composites.

Circularity goals for the system will be investigated.
System Goals: Design for disassembly, Ease in Manufacturing
Material & Component Goals: Reusability Potential, Multiple Useful lives through Repurpose.

Objective for Phase 5 –

- Evaluate and compare the circularity potential of the biocomposite cladding with a conventional cladding system as per the iterations of material, method of manufacturing and design to achieve a desired geometry.

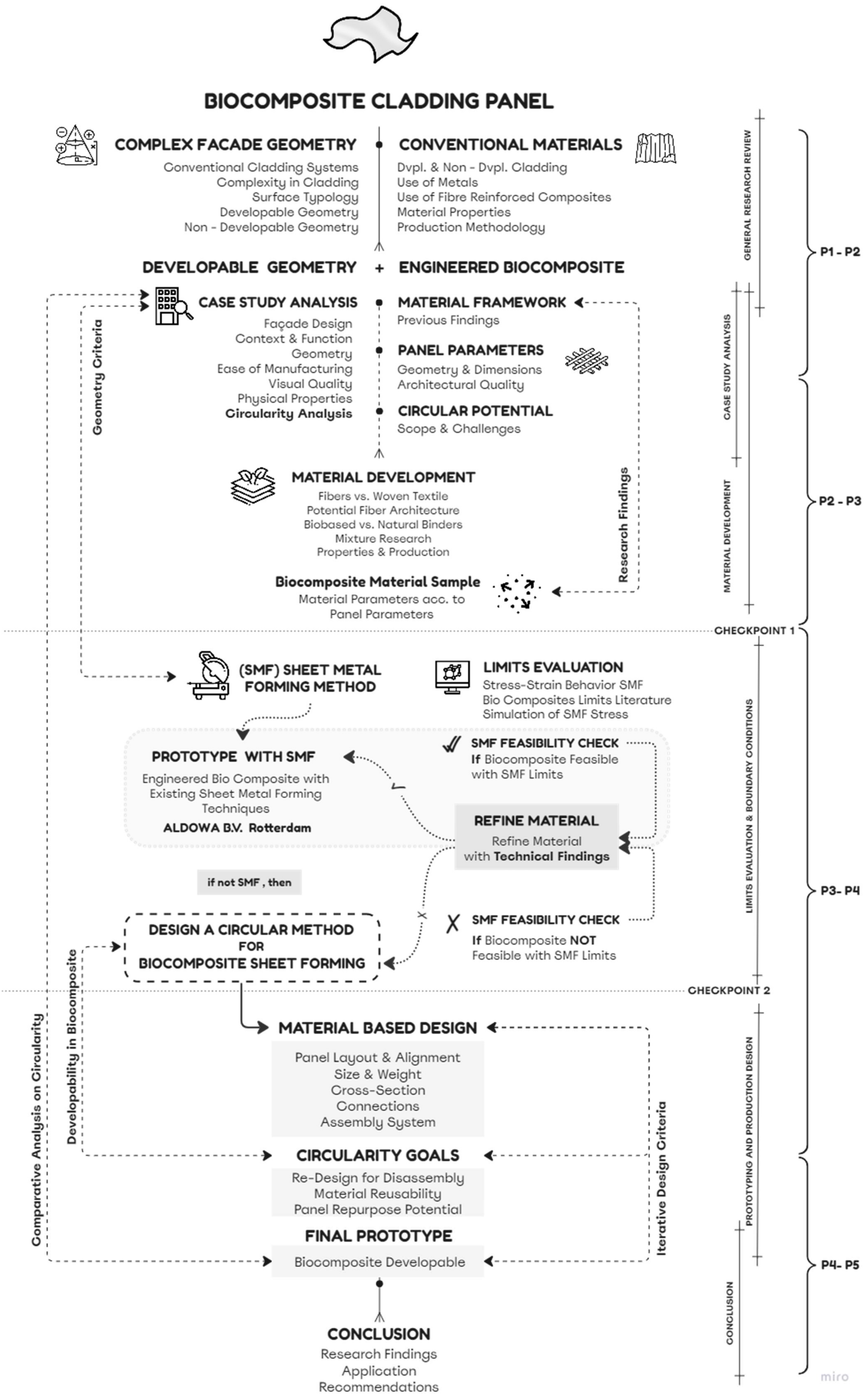
Phase 6: Application & Conclusion

The last phase focuses on summarizing details of the prototyped biocomposite panel and its application to the case study. Detailed facade drawings, installation methodology, and risk scenario analysis will be portrayed. The aim is to evaluate the applied framework followed by the set of recommendations for future development of developability in Engineered Biocomposites.

For Phase 6, we will conclude with application and recommendations, so the final objective is –

- Map all differences across scales of material properties, effective production of components and system-level design with the biocomposite prototype vs. case study.

Planning Diagram – Continued on Page 8.



BIOCOMPOSITE CLADDING PANEL
COMPLEX FACADE GEOMETRY
Conventional Cladding Systems
Complexity in Cladding
Surface Typology
Developable Geometry
Non - Developable Geometry
CONVENTIONAL MATERIALS
Dvpl. & Non - Dvpl. Cladding
Use of Metals
Use of Fibre Reinforced Composites
Material Properties
Production Methodology
DEVELOPABLE GEOMETRY + ENGINEERED BIOCOMPOSITE
CASE STUDY ANALYSIS
Façade Design
Context & Function
Geometry
Ease of Manufacturing
Visual Quality
Physical Properties
Circularity Analysis
MATERIAL FRAMEWORK
Previous Findings
PANEL PARAMETERS
Geometry & Dimensions
Architectural Quality
CIRCULAR POTENTIAL
Scope & Challenges
Geometry Criteria
Research Findings
MATERIAL DEVELOPMENT
Fibers vs. Woven Textile
Potential Fiber Architecture
Biobased vs. Natural Binders
Mixture Research
Properties & Production
Biocomposite Material Sample
Material Parameters acc. to
Panel Parameters
CHECKPOINT 1
(SMF) SHEET METAL FORMING METHOD
LIMITS EVALUATION
Stress-Strain Behavior SMF
Bio Composites Limits Literature
Simulation of SMF Stress
PROTOTYPE WITH SMF
Engineered Bio Composite with Existing Sheet Metal Forming Techniques
ALDOWA B.V. Rotterdam
SMF FEASIBILITY CHECK
If Biocomposite Feasible with SMF Limits
REFINE MATERIAL
Refine Material with Technical Findings
if not SMF , then
DESIGN A CIRCULAR METHOD FOR BIOCOMPOSITE SHEET FORMING
SMF FEASIBILITY CHECK
If Biocomposite NOT Feasible with SMF Limits
CHECKPOINT 2
MATERIAL BASED DESIGN
Panel Layout & Alignment
Size & Weight
Cross-Section
Connections
Assembly System
CIRCULARITY GOALS
Re-Design for Disassembly
Material Reusability
Panel Repurpose Potential
FINAL PROTOTYPE
Biocomposite Developable
Comparative Analysis on Circularity
Developability in Biocomposite
Iterative Design Criteria
CONCLUSION
Research Findings
Application
Recommendations
GENERAL RESEARCH REVIEW
CASE STUDY ANALYSIS
MATERIAL DEVELOPMENT
LIMITS EVALUATION & BOUNDARY CONDITIONS
PROTOTYPING AND PRODUCTION DESIGN
CONCLUSION
P1 - P2
P2 - P3
P3- P4
P4- P5
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Literature and general practical preference

The literature referenced in this thesis includes scientific papers, academic journals, data resource portals, books, engineering standards, field and case reports on circularity, literature research about composite engineering, focusing on natural fibres and biopolymers.

References cited in the Graduation Plan:

Chanda, A., & Bhattacharyya, D. (2022). Introduction of the developable surface concept in fibrous composite materials. *Composites Part A: Applied Science and Manufacturing*, *157*, 106910.

Circular Economy: a smart way of using materials. (2021, November) https://www.materialflows.net/circular-economy/

Duncan, J. P., & Duncan, J. L. (1982). Folded developables. *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences*, *383*(1784), 191-205.

IEA (2022), Aluminium, IEA, Paris https://www.iea.org/reports/aluminium, License: CC BY 4.0

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Lee, G., & Kim, S. (2012). Case study of mass customization of double-curved metal façade panels using a new hybrid sheet metal processing technique. *Journal of Construction Engineering and Management*, *138*(11), 1322-1330.

Merhi, N. (2022). Natural Fiber Reinforced Composites and Façade Applications: A research on the mechanical performance of plant fiber reinforced bio-resins and its possible façade applications.

Pottmann, H., Schiftner, A., Bo, P., Schmiedhofer, H., Wang, W., Baldassini, N., & Wallner, J. (2008). Freeform surfaces from single curved panels. *ACM Transactions on Graphics (TOG)*, *27*(3), 1-10.

Shanmugam, V., Mensah, R. A., Försth, M., Sas, G., Restás, Á., Addy, C., ... & Ramakrishna, S. (2021). Circular economy in biocomposite development: State-of-the-art, challenges and emerging trends. *Composites Part C: Open Access*, *5*, 100138.

Vaudeville, B., King, M., Aubry, S., Raynaud, J., Chalaux, M., & Witt, A. (2013). How irregular geometry and industrial process come together: a case study of the "Fondation Louis Vuitton Pour la Création", Paris. In *Advances in Architectural Geometry 2012* (pp. 279-294). Springer, Vienna.

Witten, E., & Mathes, V. (2022). The European Market for Fibre Reinforced Plastics/Composites in 2021. Texdata International.

Reflection

Relevance between Graduation Topic and Master Programme

This thesis merges the two Graduation studios of AE + T i.e., the Sustainable Design Studio and Facades & Product Design Studio. Metals & Synthetic composites are widely used in the building industry, due to their structural, flexible, and optimal performance, however, metals require extraction of primary raw materials, electrical energy consumption and synthetic composites replacing metals like GFRP lose their functionality after being used, ending up as waste often burned or landfilled (Witten & Mathes, 2022).

The rising global emissions due to linear use of conventional materials due to their fast production flows for desired architectural forms is resulting in a highly complex, material and energy intensive, and damaging web of supply chains.

The thesis is an innovative enquiry into alternative materials like biobased composites, that potentially, reduce the carbon footprint at every stage of the lifecycle while minimizing waste through circular production methods. The goal is to achieve the desired geometries prominently featuring in contemporary facades today, and the results of this thesis can guide research to reduce dependence on metals and synthetic composites for complex facades.

This research will result in a circular & sustainable biocomposite cladding system for application in the building industry. On a broader level, the focus is on structural design and facade design through circularity. Both areas relate to the Building Technology Track as it aims to extend the knowledge of Circular Façade Cladding and the ongoing research on Engineered Biocomposites in TU Delft.

Social & Scientific Relevance

The circular-built environment aims for sustainable development of both the economy and the society without harming the natural ecological cycles. According to the extensive observations seen across industries, (Circular Economy: A Smart Way of Using Materials, 2021) product design plays a key role for extending product lifespan and closing material loops.

The Built Environment needs tangible research & development in alternative materials with circular principles of looping resources for a smooth transitioning from linearity of use, by improving the productivity of biobased materials and products, reducing the extraction of fossil fuel based resources and the generation of waste.

The material-based design exploration of this thesis will focus on the limits and possibilities of Natural Fibre reinforced composites through a realistic case study. To address design strategies like design for disassembly, ease of manufacturing, reusability and repairability, as well as upgradability for façade cladding of engineered biocomposite material will be scientifically relevant, as it has not yet been reported by practice or literature.

Since, the material 'developability' of biocomposite sheet forming is still emerging for façade applications, an enhanced façade specific use of biobased constituents through the research will bridge the gap between building trends, circular operations and biobased composites.