ENGINEERING BIOCOMPOSITES

FOR CIRCULARITY IN CLADDING SYSTEMS WITH COMPLEX GEOMETRY

Master Thesis Research

Samanwita Ghosh

Class of 2023

MSc in Architecture, Urbanism and Building Sciences (Building Technology)

Delft University of Technology | TU Delft

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Mentors

Dr. Olga Ioannou & Dr. Mauro Overend

Building Product Innovation + Structural Design & Mechanics

TU Delft

> “ With growing recognition of ecological failure, our survival demands we consider ethical responsibility in the direction of research and development of new realities. ”
>
> Dalai Lama

ACKNOWLEDGEMENTS

Words alone can not acknowledge the efforts of those behind this document. However, I will try my best.

By the cover, this may look like a thesis report on a subject I have researched for eight months, but for me, it carries all hints of the highest summits and the deepest valleys from a phase that was a definitive turning point of my 26-year-old life. Fulfilling a master's thesis was a pursuit I hadn't fully comprehended till I had to live it because I had seemingly given my personal best to achieve TU Delft in 2021. So this was the universe's plan to show me that I knew very little of my limits and how everything in life is some form of collective work. Therefore, I acknowledge every thought, opinion, interaction, exchange and silent favour in the past two years that has culminated in the successful completion of this project, along with the entourage of support that has been with me throughout.

Away from home, as I left behind every familiar constant, my parent's outlook on life led me even to attempt an MSc, as their unwavering belief guided me like a lighthouse in a rough sea. Maa & Baba, thank you for staying strong for our little family while I was 7000 km away. This degree, and whatever is to follow because of it, is all yours. Baba - your work ethic and discipline continue to be my benchmark. Thank you for the privilege to access your genius intellect and your after-office free time for hours of doubts & troubleshooting. I lived by your loving & realistic affirmations. Maa, thank you for the meditative mornings where you gave your calm & strength over calls while I grounded myself for facing the day. You brought peace to this whirlwind journey while giving me love and hope every day that it will be okay.

This 180-page thesis would not have been relevant even for a paragraph if it wasn't for the sheer brilliance and countless hours that my exceptional guides Dr-Ing. Olga Ioannou and Prof. Dr -Ing. Mauro Overend handed me without a sliver of hesitance. Their leadership conceived the novelty of this topic even before I did. I went to them with long lists of thoughts, and they both patiently walked with me through the depths of my reasoning to thread the needle and only bring out the best in this research for everyone to see. This document is a craftwork of their invaluable experience as professors and their collective ability to sift through the best in unbaked thoughts and unsure steps of first-time researchers. Prof. Mauro - your unparalleled ability to find logic in my thoughts and your enthusiasm for the soul of this research have given meaning to this work from Day 1. Prof. Olga - while you saw right through my unsaid and unwritten, strengthened me personally to face my weakest links, regularly cheered me through my lows & gave hugs that grounded me, I thanked my fortune for having found a confidante in a leader.

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Thank you to my friends who believed in me and, for no personal gain of theirs, always offered the comfort and warmth of friendship away from the screens & the labs. Mohith, for looking out for me & showing me the value of little habits adding to big plans. Our conversations and our library days shaped this thesis. Nadine, for believing in me & my ability to do better while nurturing our friendship, despite not seeing me for days. Aneesha, for always giving sound advice, and being a patient ear, one call away. Jelle, for offering me perspectives each time I needed clarity. Koen for the hugs, and Ramya for all the affirmations right when I needed them. Anurag, for mentoring me through the start of this thesis & for reminding me of my true potential.

At last, I thank my inner child for not giving up and never choosing the easy way out.

"And once the storm is over, you won't remember how you made it through or managed to survive.
You won't even be sure whether the storm is really over. But one thing is for certain.
When you come out of the storm, you won't be the same person who walked in, and that's what the storm is all about."

- Haruki Murakami

GLOSSARY

Cladding	The outer surface comprising non-loadbearing components anchored or fastened to a frame or a building.
Layer	Each surface is assembled one at a time to serve different functions of the cladding system.
Panel	A component, generally weather-resistant covers the external layers of the system.
Connections	Some elements are responsible for joining the system (panel layer, flashings, insulative layer) to the main structure.
Backing Wall	A support structure/frame/wall to secure the cladding and sub-layers.
Facade	The designated elevation/surface of a built form's outer appearance.
Rainscreen	The outer segment of the cladding system, separated by a layer of water-resistant insulation, creates an air cavity allowing rainwater drainage & ventilation.
Opening	Avoid connecting the external environment to the indoor building environment, provisioning access to ventilation, daylight or conveyance.

ACRONYMS

2D	-	Two Dimensional
3D	-	Three Dimensional
AEC	-	Architecture, Engineering, and Construction
Al	-	Aluminium
ASTM	-	American Society for Testing and Materials
CAD	-	Computer-Aided Design
CAM	-	Computer-Aided Manufacturing
CNC	-	Computer Numerical Control
CO_2	-	Carbon Dioxide
EU	-	European Union
FEA	-	Finite Element Analysis
FRP	-	Fiber-Reinforced Plastic
GFRP	-	Glass Fiber Reinforced Plastic
GHG	-	Greenhouse Gases
GWP	-	Global Warming Potential
H_2O	-	Water
LCA	-	Life Cycle Assessment
LCI	-	Life Cycle Inventory
MPa	-	Mega Pascal (a unit of pressure)
NFC	-	Natural Fibre Composite
NFPC	-	Non-Fibrous Polymer Composite
NFRP	-	Natural Fiber Reinforced Plastic
PLA	-	Polylactic Acid (a type of biodegradable plastic)
PMC	-	Polymer Matrix Composite
RFI	-	Resin Film Infusion
RTM	-	Resin Transfer Molding
UV	-	Ultraviolet
UTS	-	Ultimate Tensile Strength

ABSTRACT

This research, structured in a six-phase iterative framework, decodes the rationale behind complex facade geometries & their dependence on conventional materials. Parallel with rising climate consciousness, the built environment is searching for mechanically competent, lower-impact material alternatives in the facade sector compatible with existing production infrastructure.

Literature finds potential within emergent natural fibre-reinforced polymers that fit the bill.
As the pairing of Flax fibres and PLA constituents emerges as the best scientific fit,
commercial facade products with natural fibre reinforced polymers do not exist yet.

The review identified a significant research gap in fibrous biocomposites; despite existing research on the economic composite sheet-forming techniques, complex structures using developable surfaces on fibrous composite materials are yet to be reported.

This study re-thinks conventional cladding systems, connects the research gap to the built environment's quest and questions the viability of biocomposites as sheet materials for facade applications.

The methodology involved empirical inquiries at every level in developing a fibre-reinforced biocomposite with the geometric capabilities required of conventional facade material standards. The system design led to a 100% biobased laminate material – a Flax-PLA biocomposite – capable of adapting to developable surface geometries.

A systematic approach was developed using sheet-forming concepts to evaluate the ability of the biocomposite to be reshaped without compromising its structural integrity. Positioning the research with circular R-strategies, this study documents the pioneering attempt for continuous natural-fibre composites, demonstrating developability as an intrinsic material property never proved.

Key findings upon an extensive testing program reveal that the biocomposite retains its original strength and durability even after reshaping, demonstrating its potential for a circular loop. A lifecycle impact assessment and comparative analysis benchmarked the material with virgin aluminium sheet metal, showing promising carbon equivalent savings using the flax-PLA panels. The biobased panels present significantly lower overall implications, even considering their current shorter service life, which can extend soon.

The findings demonstrate the feasibility of Flax-PLA composites as a circular and biobased alternative to conventional cladding materials. Forming and reshaping these panels into flat sheets without distortion allows for reusability and repurposing, retaining their embodied energy across multiple life stages. This paper proved developability with a scalable strategy as a catalyst for future research on biobased materials and to strengthen their presence in the built environment.

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01

research **framework**

This chapter introduces the **scope** of the research, identified **problems** & **objectives**.
The phasing of the methodology is according to **scientific workflow** & **timelines**.

1.1

Background

Building **Skin**

The ‘skin’ is primal for survival & upkeep, be it a building or a natural being (Sandak et al., 2019).

Façades and nature’s defence barriers, the skin, shells, and membranes, draw parallels with each other due to their evolutionary purposes to multitask & shield the host from external factors.

Documented history describes humans who learnt from nature, as in the analogy and constructed crude shelters with indistinct surfaces. Façades, as interpreted today, were a mere by-product of the barriers from early shelters. These initial façades stood as the structural skin, creating two environments: external & internal, securing spaces for human comfort (Addington, 2009).

The objective of human safety influenced all materials used in facades. The choice had always depended on the material’s ability to counteract the influence of various environmental factors in the given climate zone.

Nomadic humans settled with permanent shelter construction, and simple bio-based materials like adobe replaced masonry and other robust materials. However, the trend of permanent construction led to the scarcity of materials, like stone, resulting in progressive shifts with practical alternatives, like clay-fired bricks (Sandak et al., 2019).

The primary motivation shifted from human safety to protecting valuable structural skin from harsh environmental conditions. The importance of structural skin demanded strategic protection. Thus facade coverings were conceived. Some materials intentionally differed from the structure, while some originated from wall materials.

From the simplicity of external finishes like plaster and daub, endless iterations have been generated worldwide for façade materials & construction techniques. Consequently, the functions of façades acclimated in response to emerging science while adapting to the directives of users & the dynamics of regions led to the sophisticated development of façades and their cladding.

Trend **Shifts**

The advent of geometry & mathematics caused the first paradigm shift in façades across the eastern and the western world. It ushered in the expansion of modern architecture, characterised by different building styles, proportions and classical orders (Bellone et al., 2017; Sandak et al., 2019).

Gradually, each century saw an era of signifying aesthetics, leading to buildings creating identity and importance. Even before modern means of communication, the external skin could express the intangible elements of power & prominence through architectural complexity (ibid.)

Kolarevic (2001) noted that the Architecture, Engineering & Construction (AEC) industry had a long-standing design practice of creating for buildability. He remarked that euclidean geometry designs propagated due to the availability of straight-edge, standard drawing instruments for 2D planes. The replacement of tools and means of representation shifted as the need to draw with more straightforward, editable tools such as computer-aided 2D design programs emerged.

The latest advances in the digital age of CAD linked with computer-aided manufacturing (CAM) technologies have reconfigured the traditional relationship between initial conception and final production. Today, the development of 3D modelling surfaces & elements for building skins is possible via modelling NURBS (non-uniform rational B-splines) that allows architects to digitally create complex three-dimensional geometries for expressive aesthetics (ibid.)

Complex **Geometries**

A formal departure from basic normative geometries has established a broad research interest in material capacities (Pantazis, 2019). Designing spatial effects with geometries requires a quest for new materials and production possibilities (Kolarevic, 2001).

Due to this interdependence, complex geometries have emerged as one of the most striking trends in contemporary architecture, creating widespread research interest (Pottmann et al., 2008).

1.2

Scope of Research

Articulating the complex geometries and identifying a compatible strategy for production is far from being a linear & deductive process (Vaudeville et al., 2013).
It is a challenge to pick an appropriate pairing of material & production that preserves uniform quality as designed for the three-dimensional panel/envelope (Kolarevic, 2001).

The approach required to solve this challenge and associate geometry, materials and industrial processes calls upon many stakeholders' interdisciplinary efforts and collaboration (Vaudeville et al., 2013).

Production **Challenges: Complex Geometries**

Industrial processes have their own rules & limitations as they rarely fit highly irregular geometry features in complex facades. This gap is embedded as we seek to mesh together two independent logics - of architectural form & the means of production. So, it is necessary to approximate and re-work both form and production until they fit. (ibid.)

At the same time, the formal possibilities of the available shaping methods often demand **rationalisation** or **economical redesign** of the varied geometries in facade designs (Pottmann et al., 2008).
The overall energy & resources spent for a project ranges from the minimum for flat straight, singly bent, to the maximum for doubly bent & freeform, eventually depending on the surface typology of the facade panels ordered according to structural considerations (Lee & Kim, 2012 ; Ock, 2021).

Rationalisation & Developability

If ordered panels are **planar or one-way bent** geometries, briefly called '**developables**', the accessible machinery and the qualifying materials make it economical.
Planar sheet materials qualify as being easy to form flat or singly bent panels due to their '**developability**', i.e. the ability to bend along a single curve geometry (from now on, '**developable**') and unbent back into a plane 2D sheet without signs of distortion/creasing after tooling. (Duncan & Duncan, 1982).

The compatibility of developable geometry with the economical sheet material has the attributes of cheap fabrication due to the widespread and streamlined optimisation of centuries old traditional smith working methods (Bowen et al., 2022) reinforced by aerospace, automotive and appliance sectors now informing the AEC industry.

Therefore, it is desirable to **rationalise** or approximately achieve a freeform shape through developable segments of single curved panels.

Using the accessible and easy-to-approach sheet forming infrastructure is cost-effective and scalable as otherwise panelling with double-curved or non-developable geometries incurs a high cost of manufacturing moulds and other auxiliary devices (Pottmann et al., 2008).

Material **Limits : Complex Geometries**

Material selection for facade cladding is influenced by the overall performance requirement of the facade and its building (Smith, 1988) and the aesthetics as designed. However, the resistance of the intended material to meet the geometric demands of the facade has a considerable impact on the energy required for production, directly proportional to the overall embodied energy of the facade.

The plasticity of metals easily crosses limits, risking brittle failure if stretched or bent in two-way curves. Thus metals need to be effectively sheet formed for non-developable geometries. Even if a unique system can configure double-curving metal, the technology is capital-intensive, and the process used in the current literature has high operational and fabrication costs (Lee & Kim, 2012).

The extraction, production and fabrication of the most widely used metals, like aluminium, cause irreversible damage through high GHG emissions and nitrification of soil & freshwater, quantified through various scientific studies (IEA, 2022).

Composites

New materialities, namely glass and carbon fibre-reinforced composites, emerged to curb metals' impact, dependence and production dilemmas (Kolarevic, 2001).
However, studies that evaluate and quantify their waste-inducing production techniques, high embodied energy, and non-repetitive moulding systems call for future composites with sustainable constituents and circular production methods.

Numerous studies show promise with flexible or adaptive formwork (Henriksen et al., 2016) or incorporated moulds (Vergara et al., 2017), but these adaptive methods are yet to achieve scalability in mass production.

1.3

Problem Statement

Established **Context**

With rationalised, i.e economically panelised facades, literature proves that through developables, one can achieve the most complex forms without specific 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.

Through time, progressive sheet metals qualify all parameters for facade cladding, and available machinery of sheet forming (e.g. stretch bending/roll forming) optimally exploits the plastic deformation offered by metals. Thus, the sheet-forming industry is more suited to metals due to the lack of equally versatile and fracture-resistant material.

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.

Parallelly, in the latest report by IEA (2022), the global aluminium subsector needs to be on track with Net Zero Emissions in 2050. The direct emissions from aluminium have been steadily rising, driven by increased production and reliance on aluminium industries.

Conversely, developing composites to replace metals, such as reinforced composites like GFRP and CFRP, is structurally viable and lightweight for double-curved moulding in weight-critical applications like facade cladding.

They allow control over material properties, as engineered fibres, matrix & interlayers allow specific functions. Synthetic composites like GFRP are cheaper than metals, durable, stable, lightweight and have industry-wide applications resulting in continually rising production, with synthetic glass fibres used in 95% of all fibre-reinforced composites.

Predictably, all complex facades using GFRP and similar high-value synthetic composites will lack professional disposal after reaching their EOL, landfilling in unsustainable ways.

Until a globally applicable end-of-life scenario is found, facade cladding with synthetic fibre composites lacks reusability and second-life potential due to their synthetic and highly non-recyclable constituents.

With climate vulnerability, depleting fossil fuels, increasing landfills and rapid urbanisation, there is a critical need for the next generation of sustainable alternatives for building materials. Materials independent from petroleum-based origins are on priority by European Union experts, seconded by United Nations' sustainable development goals.

The present literature confirms a reasonable opportunity through biocomposites that, for specific applications, natural fibres with bioplastics demonstrate competitive performances compared to the synthetic fibre-matrix composite (Merhi, 2021).

These bio-composites, first developed in 1908 with lignocellulosic fibres, combine reinforcement and matrix from natural or biobased origins.

Biocomposites present a renewable and biodegradable alternative to the increasingly used fossil fuel-based materials for complex facade cladding (Shanmugam et al., 2021).

> "**Literature & practice is yet to report the application of complex geometries in natural fibre composites using developable surfaces; hence the desired property of developability in biocomposites and their enhanced potential as a circular component is underexplored.**"

1.4

Research Questions

This research focuses on contributing towards the innovation of fibre-reinforced biocomposites and diverting from fossil-fuel-based materials like aluminium to biobased constituents. The main goal is to explore biocomposites' circularity potential, experimentally validate their ease of developability, and discover consequent properties applicable to façade cladding systems.

Main Research Question is formulated as:

> "**How to engineer a fibre-reinforced biocomposite cladding panel for complex geometric facades?**"

Sub-Questions according to various themes are:

Geometry Analysis in Façade Cladding

1. What does the term "complex geometries" signify in the context of facade cladding systems?
2. Can more environmentally materials be used for producing complex geometry cladding?

Case Study & Material Study

3. What are the attributes of state-of-the-art aluminium cladding with developable geometries?
4. What are the properties of natural fibre-reinforced biocomposites applicable to facade cladding systems?
5. What are the engineering standards and limits involved in fabricating developables of fibre-reinforced biocomposite using sheet metal forming?

Production & Prototyping for Circularity

6. What is(are) the effective method(s) of production for shaping biocomposites into a developable panel?
7. What are the differences in material, manufacturing and component scales between biocomposite & aluminium panels for a desired geometry?

1.5

Objectives

"The concept of **developable** surfaces has not been implemented for fibrous composites." (Chanda & Bhattacharyya, 2022, p. 1). If the 'developability' of biocomposites is proven, the facade component can achieve circularity 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 valuable lives. Materials from biobased origins shall reduce the carbon footprint at every lifecycle stage while minimising waste through circular production methods.

The research-by-design approach will be a practical and tectonic design exercise.

There are two key quests:
biocomposites' potential to be a circular alternative as a cladding panel and the material behaviour of biocomposites for developing complex geometry.

Initial **Query**

The initial design assignment is to find suitable fibre architecture and matrix compositions of biocomposites. The possibility of being formed into panels using current sheet metal forming techniques for researching its scalability potential in existing infrastructure requires numerical validation through simulations.

Research **Intent**

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

This research will probe the possibility of shaping developable geometries with bio-composites and whether their inherent strength qualifies them for cladding applications.

1.6

Boundary Conditions

The starting point will be to identify the hierarchy of complexity in the geometry of modern cladding systems. The constraints preventing the use of potentially biobased or sustainable alternatives are also a parallel starting point of the research.

A case study selection will map the practical observations and attributes of material, manufacturing & cladding system design.
In this case, for a developable geometry, attesting to the 'developability' of the material, hence the circularity of the material.

Existing research about flax-fibre reinforcement with biobased resins will be forwarded and built upon for the material review. Several matrix material mixtures and diverse fibre architectures for reinforcement will be examined & prototyped to achieve competitive performance on a material level compared to the case study panel.

The circularity potential after shaping and the potential to be functional for multiple useful lives or additional purposes will be studied.

Limitations

The research is limited to available production or efficient composite forming methods and will not undertake industry methods for double-curved shaping. A developable biocomposite panel, if formed, can be assumed to be viable for rationalized or approximated free-form/double-curved facade geometries.

The scope of composite engineering will encompass a summary of available biobased resins and natural binders, along with woven/aligned flax fibre reinforcement available or feasible to prototype.

1.7

Expected Outcomes

Suppose the biocomposite can be plastically deformed using the existing infrastructure of optimised sheet-forming techniques. In that case, we can achieve specific properties desired from metals while retaining the flexibility in properties desired from composites for specific facade requirements.

The empirical performance characterisation of natural fibre-reinforced biocomposites is yet to be researched in detail. The circularity potential of these biocomposites, in regard to the limits of cladding functionality in building envelopes, will be a part of this evaluation.

Expected Research Flow:

1. Evaluate surface geometry complexity and typology in current facade cladding systems.
2. Contrast conventional materials' circularity within complex geometry cladding systems.
3. Study an aluminium cladding case for material attributes and design methods.
4. Investigate compatibility of biocomposites with existing production techniques.
5. Identify suitable natural fibre structures and biobased matrix for facade-appropriate biocomposites.
6. Prototype and test biocomposite fabrication akin to aluminium panel production.
7. Develop an efficient, circular sheet-forming method for shaping biocomposites.
8. Compare biocomposite and aluminium panel properties, component production, and system-level design.
9. Assess circularity potential of biocomposite versus conventional cladding systems, considering material, production, and design iterations.

1.8

Approach & Methodology

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

Phase 1
Literature Review & 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.

Phase 2
Case Study Analysis
Aluminium Cladding

A case study of the MOL Campus Budapest (2023) is selected and analyzed to provide a realistic scenario in defining structural, visual, and assembly criteria of the façade cladding system with developable geometry. Contact made with Scheldebouw for a detailed investigation.

Phase 3
Material Study & Limit Evaluation
Fibre Reinforced Bio Composite

The focus of this phase is two parts. Suitable fibre architecture and matrix compositions will be studied. The study will be forwarded on previous findings for applicability to facade cladding and further regarding the geometry of the case panel. The 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.

Phase 4
Prototyping & Production Design

The final concept for the set-up will be formed based on technical findings. The technical findings of Phase 3 will refine the material and guide in developing a new and suitable method of composite sheet forming.

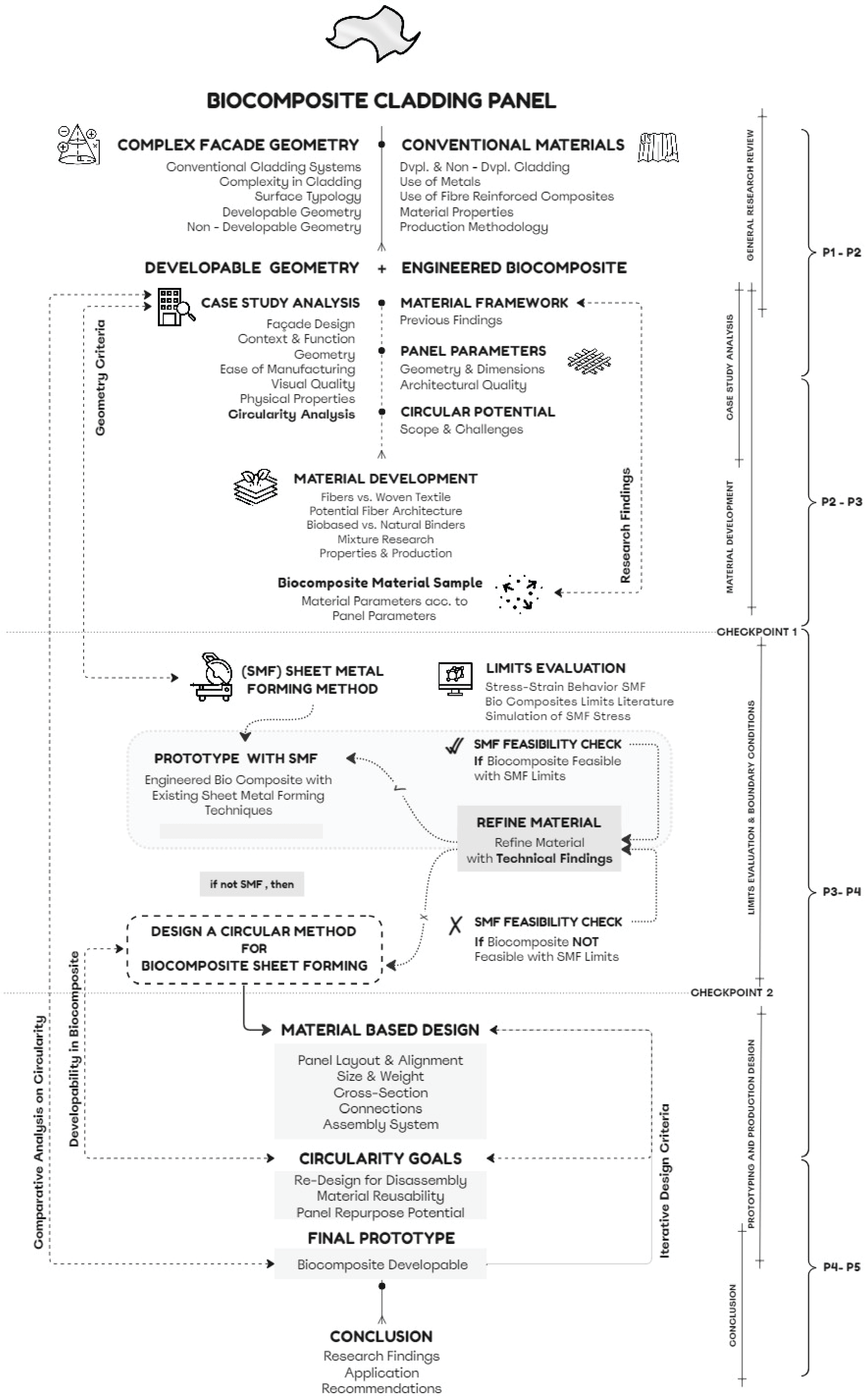
Phase 5
System Refinement & Comparative Analysis

This phase is essential for Material Design Iterations. The goal is to keep the geometry constant and iteratively experiment with the panel layout, size, weight, cross sections, physical properties, compositions and qualities to evaluate the limits of biocomposites—circularity goals to be investigated for the system.
System Goals:
Design for disassembly, Ease in Manufacturing
Material & Component Goals:
Reusability Potential, Multiple Useful lives through Repurpose.

Phase 6
Application & Conclusion

The last phase summarises details of the prototyped biocomposite panel and its application to the case study as a circular biocomposite.

The aim is to evaluate the applied framework followed by recommendations for future development of developability in Engineered Biocomposites.
For Phase 6, we will conclude with application and recommendations.


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
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
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CONCLUSION
Research Findings
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GENERAL RESEARCH REVIEW
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LIMITS EVALUATION & BOUNDARY CONDITIONS
PROTOTYPING AND PRODUCTION DESIGN
CONCLUSION
P1 - P2
P2 - P3
P3- P4
P4- P5

1.9

Relevance

Academic **Relevance**

This thesis merges the two Graduation studios of AE + T, i.e., the Sustainable Design Studio and Facades & Products Design Studio.

The structural, flexible, and optimal performance of Metals and Synthetic Composites are widely applicable to building products. 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.

The rising global emissions due to the linear use of conventional materials and fast production flows for desired architectural forms result 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 featured 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.

Scientific **Relevance**

The circular-built environment aims for sustainable development of both the economy and society without harming the natural ecological cycles.

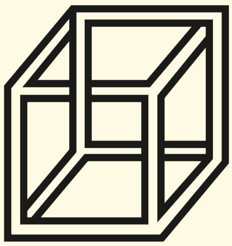
According to the extensive observations seen across industries (Circular Economy: A Smart Way of Using Materials, 2021), product design plays a crucial role in extending product lifespan and closing material loops.

The Built Environment needs tangible research & development in alternative materials with circular principles of looping resources for a smooth transition 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.

The objective is to make two main contributions to material research and building practices.

Since the material 'developability' of biocomposite sheet forming is still emerging for façade applications, the research will bridge the gap between emerging façade trends, circular manufacturing methodology and biobased composites.



02

complex geometry façade **cladding**

This chapter introduces the **significance** and **aspects** of complex geometries in facade cladding systems.
Review presents the surface **typology** & corresponding **attributes** of the current cladding **practices**.

2.1

Significance

Façade **Cladding**

“A building, if properly conceived, contains several layers of longevity as-built components” (Brand,1995); the facade is the fundamental layer that can influence the longevity of other building layers.

The facade is a multilayered system forming the primary envelope or the skin layer. (King, 2017). As Brand (1995) emphasised, the skin acts as the main visible boundary, connecting function and aesthetics, in the role of an envelope as the first line of defence for the indoor environment from atmospheric elements (Addington, 2009).

Facade Cladding stands the outermost skin layer, mainly weathering environmental damage, water, force and time. As a sub-system of the overall facade, it performs multiple functions as an interface for thermal, acoustic and fire-resisting properties.

However, the prominence of cladding lies in its primary role as a visual and user-facing interface, thus serving as a medium to distinguish built exteriors from one another (Kamal, 2020).

While the meaning of cladding refers to installing one material over another; the intention of protection and aesthetics is purely in the context of the built environment. Cladding systems protect the underneath structural wall system material with an exterior layer. As a non-load bearing component, it transfers loads from wind, impact, snow and self-weight back to the structure (BSF, 2021).

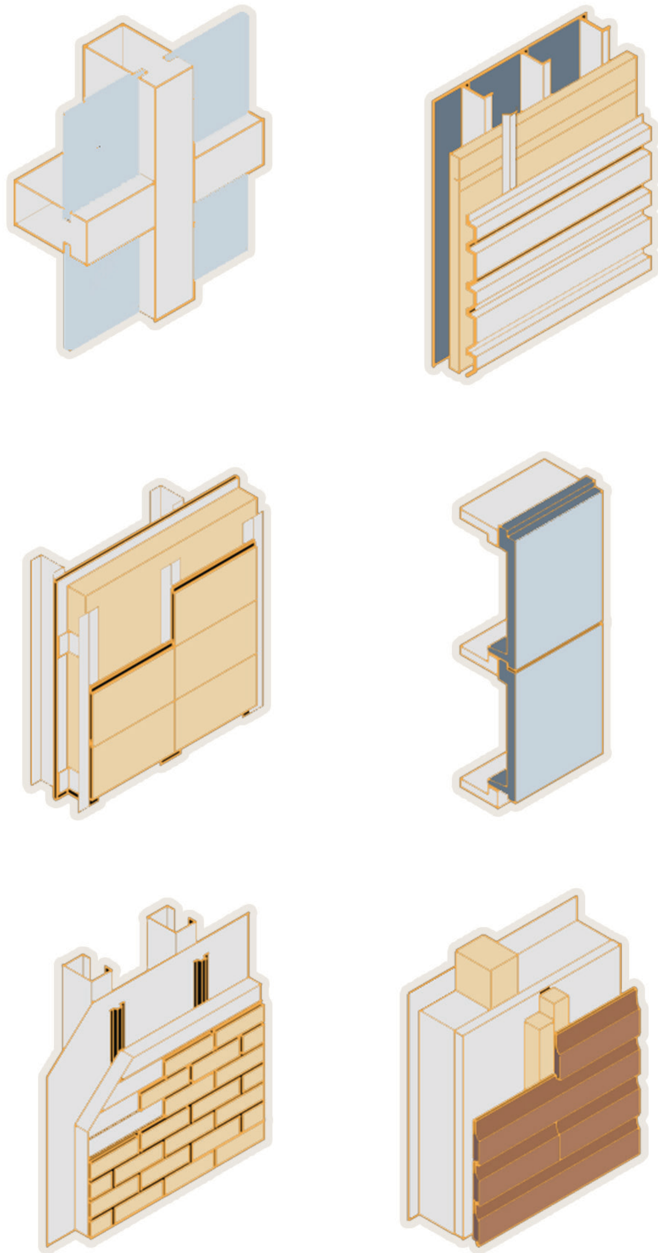


Figure 1 : Illustration: **Own**
Different Types of Conventional Cladding Systems

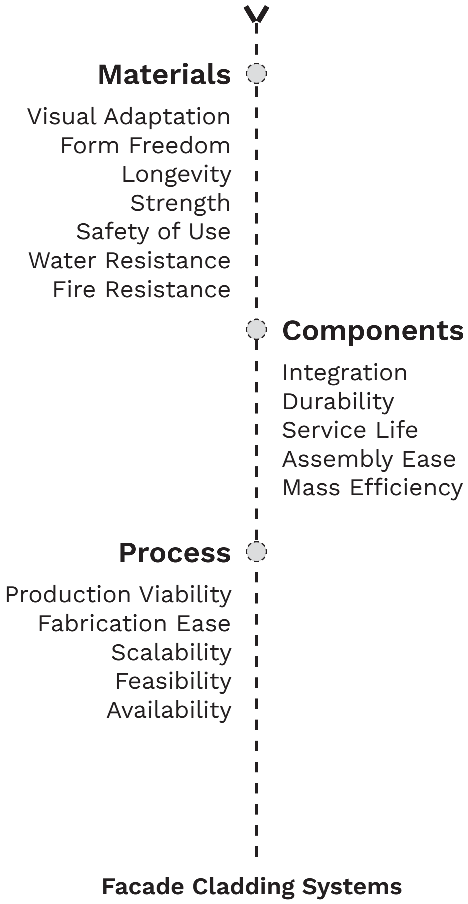
2.2

Aspects

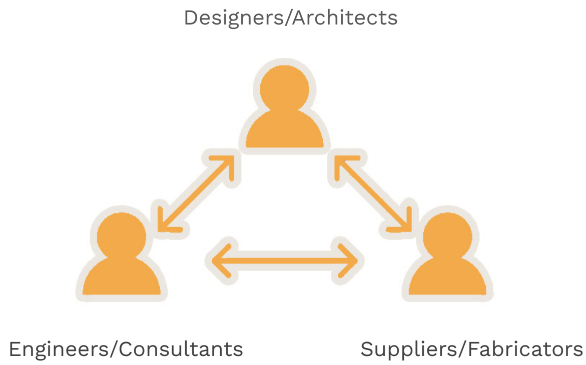
Current **Systems**

Determining the design conditions of facade cladding requires dissecting the logic of systems thinking in cladding systems. According to a report by Bekkering et al. (2021) some considerations constitute elements to form a coherent whole that is critical in every design decision. All stakeholders, as decision-makers, affect the industry and the built environment, as individual materials, building components, and techniques collaborate to realise a design.

The investigation has three main aspects of understanding the prerequisites for building products and the reasoning behind design trends & standards (ibid.) For this review, we shall determine facade cladding systems through these aspects.



Stakeholders in **Cladding Design**



Moving from the simpler times, the sophistication in cladding now ranges from enabling air tightness (e.g., curtain walls steel, aluminium, & glass) to controlling (e.g., ventilated cladding) unsafe water ingress (Sandak et al., 2019) along with the complexity of highly geometrical surfaces.

Functions - Barriers **Flow**

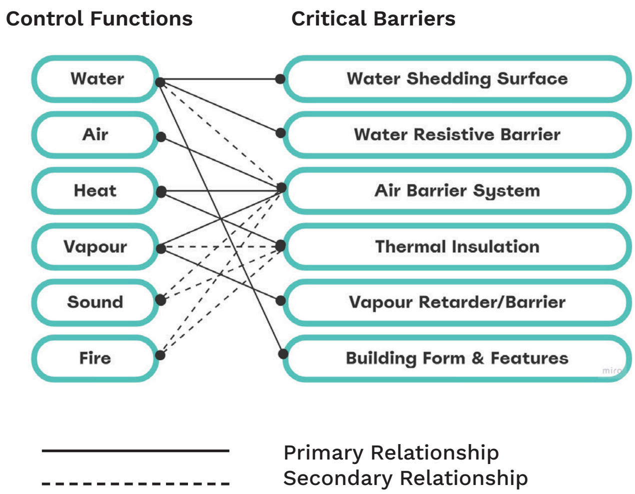


Figure 2 : Flows between Control Functions vs. Critical Barriers of Cladding, Source : **Own**

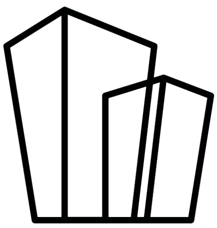
2.3

Conception Drivers

Cladding can be endlessly suited to diverse functionalities. Therefore, the industry fabricates from most material classes, and each dominant function-material pair has distinct pros and cons. The cladding system employed in a building depends on the functionality and climatic needs. The facade system is an essential response to the elevation and exposure of installation, i.e. the project context.

Each project generates imperatives, but usual themes remain constant as conception drivers for cladding systems with panels (King, 2017).

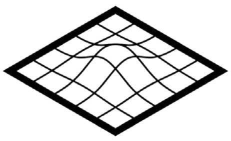
Facade Design



1. Built **Form**

The design sector continually influences the building industry by pushing the limits of the building's Form and envelope (Najjar, 2013). The emergence of digital technologies has industriously assisted designers in manipulating surface geometries to achieve bespoke architectural outcomes for 20 years now.

Geometry, if complex, steers material choices for ease of formability, fabrication and long life span. Geometrical limits inform material choices & fabrication of the selected cladding system (King, 2017). It implies that panelling or cladding for analytically complex facade structures has additional technical limits and requirements compared to cladding for planar building surfaces.

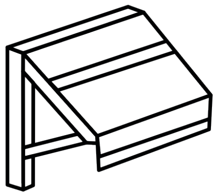


2. **Panel Geometry**

Geometric complexity translates across scales in the AEC industry (Pantazis et al.,2019); therefore, it demands structurally versatile materials, namely Metals & Alloys, Technical Ceramics & Fibre Reinforced Composites.

These materials conventionally support geometrical complexity by performing efficiently on levels of individual panels for various building forms. Panel configurations are subjectively customised to project parameters. For conventional cladding systems, panel geometry depends on the surface typology of the subject wall system, amongst other factors, dictating the surface typology of the unitised panels, if any.

This interdependency has resulted in geometry being a key parameter for the initial design process and overall materialisation for high-performance facades.



3. **Functionality**

Classifying the cladding spectrum can vary from plain light steel walling to complex rain-screen systems. However, the selection of the cladding system should address the performance requirements for the overall facade and the type of support system best suited to the aesthetic and functional requirements of the building (Smith, 1988). Therefore, designing the functionality of cladding, in terms of required thermal properties and environmental characteristics of the building design, drives the conception of the building envelope as a whole (Gaspar et al., 2016).

The functions defined for the cladding system can determine the type of cladding panels. The classification below demarcates panels by the degree of function vs sub-layers.

Degree 1 Aesthetic Value Addition

Cladding systems intended for aesthetic value addition have minimal conditions and the least sub-layers. They may be aesthetically spaced and may need to cover the structure behind them entirely.

The outer panel material is anchored without any insulation layers. These panels may be planar or geometrically complex.

Degree 2 Wall System Protection

Cladding systems intended for wall system/structure protection from nature have durability requirements yet also have the least number of sub-system layers. Close spacing in panels fully covers the substructure beneath and prevents crack degradation risk. The outer panel material is anchored without insulation layers and may be planar or geometrically complex.

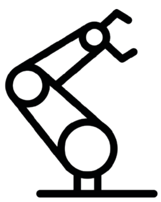
Degree 3 Sunscreen Systems

Cladding systems can shade buildings & users from intense sun exposure while providing thermal and visual comfort to the users of the enveloped building. Panels can vary in transparency and opacity and can even be perforated to diffuse harsh light. The spacing and installation of these panels vary according to daylight & indoor comfort parameters. Insulation layers do not accompany typical sun-screen panels.

Degree 4 Insulated Rain-Screens

Rainscreen * cladding shields from rain and incorporate multiple sublayers to insulate the building thermally and acoustically. However, a ventilated air cavity between the airtight, insulated backing wall generally isolates the outer skin. It allows continuous ventilation to maintain a stable temperature, resulting in an energy-saving envelope. Rainscreen panels need typical joinery to control water infiltrations. The panels are generally opaque and intact without perforations.

One can conclude that functions multiply the cladding layers required to be a system. The cladding types can vary from simple planar aesthetic systems to doubly curved panels, including water-tight insulation backing. Simply put, the degree of complexity increases with the envisioned purpose of the skin.

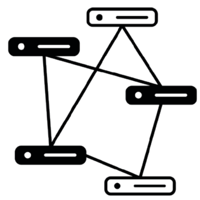


4. **Fabrication**

Kolarevic (2001) noted the tectonic consequences of complexity in highly curvilinear surfaces, prominent in contemporary facades, carry the challenge of credibility and construction, involving facade architects in the fabrication processes.

Today architects create information translated by fabricators directly into control data that drives digital fabrication equipment needed to realise complex facades (ibid).

The author even specified that the fundamental factor for the conception of a cladding system is the degree of prefabrication in the project. While integrating adjustments is critical, off-site fabrication presents more favourable conditions and avoids on-site lags leading to higher quality control, accompanied by testing (King, 2017).



5. **Production Feasibility**

Kolarevic (2001) extensively recorded strategies for articulating the tectonics of NURBS-based envelopes in his book, Designing and manufacturing architecture in the digital age.

The author identified the challenge of choosing the appropriate geometrical approximation for the as-built that can preserve the critical features of the three-dimensional form as designed (ibid).

Factors like geometric complexity, possibilities, resistances offered by intended material composition, and structural considerations primarily impact the overall project cost, thus driving the strategies.

The author also reported that the production strategy used depends on tectonics that is to be defined: structure, envelope, or a combination of the two, as the rules of constructability demand geometry rationalisation in the facade components, made to order according to cost, as straight, flat, radially bent, doubly curved, highly shaped or distorted.

2.4

Cladding - Geometry

Overview

Buildings with novel forms or facades are highly requested by clients worldwide. These demands are reinforced by the advancement in facade design & production for geometrically complex buildings, as they lend a distinctive character (Blandini et al., 2014).

Such facades regard sculptural dimensions and fragmented solid forms. Many external factors influence the realisation of highly complex surfaces, but the construction details are critical for the success of complex geometries (King et al., 2017.

Details depend on each component's material and manufacturing, which are the fundamental factors requiring careful consideration in facade design (Pottmann, 2008).

Interdependency - **Material & Manufacturing**

Each step for materialisation needs inputs from advanced design tools & generative scripts. This trend has multiple implications as it challenges the material choice in a conventional design-to-build workflow. The shaping of the materials is debatable, as there could be diverse permutations (Aubry et al., 2013).

Hence, the efficient functioning of a complex envelope depends on materials that can be practical to fabricate the details and facilitate assembly on-site (King et al., 2017). As mentioned earlier, the structurally versatile material classes, namely Metals & Alloys, Technical Ceramics & Fibre Reinforced Composites, are the subjects of continued material research to support the detailing required by complex facades. These material groups perform efficiently on levels of formability, fabrication and long life span but are high in embodied energy.

Although extending and encouraging low embodied energy materials for complex geometry is desirable, there are structural areas for improvement from a material standpoint. The several challenges to procurement, availability, long-term durability, maintenance, and regulatory requirements discourage the extensive use of possible novel materials (Bekkering et al., 2021).

Key **Notes**

Geometry is the starting point that affects all design stages, from form-finding to fabrication. (Majeed et al., 2021) To better understand the geometric theory for the development of cladding systems, a quick introduction to the basics is for reference.

1. Regular Shapes vs. Organic Shapes

Mathematical formulas define geometries, which can be plotted on a geometric graph to create standard shapes like circles, squares, and triangles. At the same time, ellipses, rectangles, polygons (pentagons, hexagons, octagons), and parallelograms are considered deviations from these standard forms. All belong to the family of geometrical shapes. However, some shapes can also be organic, and typical mathematical formulas may not be able to generate shapes produced in nature, often with irregular and asymmetrical outlines. (Majeed et al., 2021)

2. Plane Geometry vs. Solid Geometry

Theoretically, Geometry refers to 2D plane geometry (shapes) and 3D solid geometry (forms). The essential elements of standard geometries are lines and planes. When the behaviour of lines guides geometries according to their directions in the two-dimensional space (2D from now on), they are referred to as shapes or plane geometry, and when in three-dimensional space (3D from now on) are referred to as forms or 3D solid geometry. (Majeed et al., 2021)

Ching (1943) reported that dimensionality is the vital parameter distinguishing form and shape. Accordingly, the form has depth as a third dimension while the shape has only length and breadth as the two measurements.

2.5

Surface Typology - Façades

Realistically, no material can be without thickness. Hence every material ever shaped/formed for construction is a 3D form.

As forms are the resultant assembly of surfaces; so, to distinguish between forms, surface typology is critical.

Defining between planar and non-planar surfaces can guide us to surface typology. Let us assume a solid geometry with a surface and minimal thickness to visualise a standard sheet panel.

1. A surface is considered a planar surface when all vertices lie in one specific reference plane.
2. A surface is considered a non-planar surface when it has more than 3 vertices and one or more of them do not lie in the same reference plane as the others.

Surfaces & **Facade Construction**

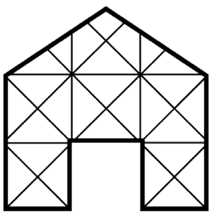
Facades are a similar part of buildings as surfaces are for solids. Lee and Kim (2012) defined panelization and rationalisation as iterative processes.

To be built, a large building surface or a regular or irregular facade must be divided into small panels.

Panelisation is the division of a large building surface into smaller panels of a constructible proportion.

Rationalisation is to optimise an economical batch size, dimension and shape for the building surface panels.

Iterations repeat; panel shapes are rationalised and vice-versa until they satisfy aesthetics, economic constraints and construction conditions.



Panelisation

Rationalisation

Planar vs. Non-Planar Geometry

Planar geometry has length, breadth and minimal thickness, with all vertices on the same reference plane. In the context of panelling, the flat or levelled cladding panels can be named planar geometry.

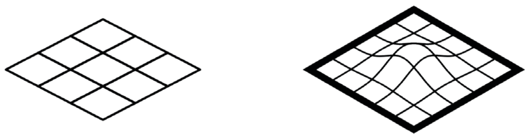
Non-planar geometry has more than one of the vertices or nodes of the principal surface in a different plane than the reference plane. The surface(s) would extrude in a (linear/curvilinear) direction different from the plane of the supporting wall system.

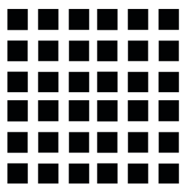
In-Plane vs. Out-of-Plane Cladding

The relation of the principal surface with the reference plane determines the typology of the panelization. Non-planar panels can, therefore, be considered out-of-plane regarding the wall system.

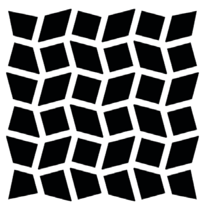
It is important to note that the appearance of extrusion in panels is subjective to the support structure's geometry. For instance, curved panels would appear out-of-plane & hence 3D in front of a flat wall system. The same curved panels would appear in-plane and non-3D concerning a wall system with similar curvature.

For this review, all panels curved and extruded away from the tangent reference plane of the anchored wall system would be considered as 3-Dimensional panels.





In-Plane



Out - of - Plane

Surface **Typology**

While planar construction is flat panels without curvatures, non-planar construction is more complex across scales of built forms to the facade.

Kolarevic (2001) prominently advocated them as 'complex curved surfaces' as a tool to create structural & space-efficient forms with desired aesthetics.

Gaussian curvature measurements often describe the typology of these surfaces in three-dimensional space. This review will analyse the primary variations of surface typology featured in contemporary facades using the Gaussian Curvature Analysis.

A surface's Gaussian curvature (κ) at any given point is the product of the principal curvatures in each direction: K = (κ 1). (κ 2) (Kolarevic, 2001).

Surface curvatures can be classified into four types resulting from the Gaussian curvature i.e. zeroclastic, monoclastic, synclastic and anticlastic (adapted from Pronk & Dominicus, 2012):

1. If Gaussian curvature is zero (κ1). (κ2)=0 & both principal curvatures are zero, the surface is considered zeroclastic at that given point so the surface is level.
2. If Gaussian curvature is zero (κ1). (κ2)=0 and only one principal curvature is equal to zero, the surface is considered zeroclastic at that given point. Examples of such surfaces are an unrolled cylinder or a truncated cone.
3. If Gaussian curvature is positive (κ1). (κ2)>0, with the principal curvatures being the same sign values. This implies the surface is considered synclastic or dome-shaped at that given point.
4. If the Gaussian curvature is negative (κ1). (κ2)<0, the principal curvatures have different sign values. This implies the surface is considered anticlastic or saddle-shaped at that given point.

Fig 1 : **Typology from Flat Surface to 3-Dimensional**

(a) Planar flat surface
(b) Zero-curve bent surface or 'cylindrical' surface
(c) Zero-curve bent surface or 'conical' surface
(d) Positive double-curved surface or 'dome-like' surface
(e) Negative double-curved surface or 'saddle-like' surface
(f) Free form surface or combination curvilinear surface

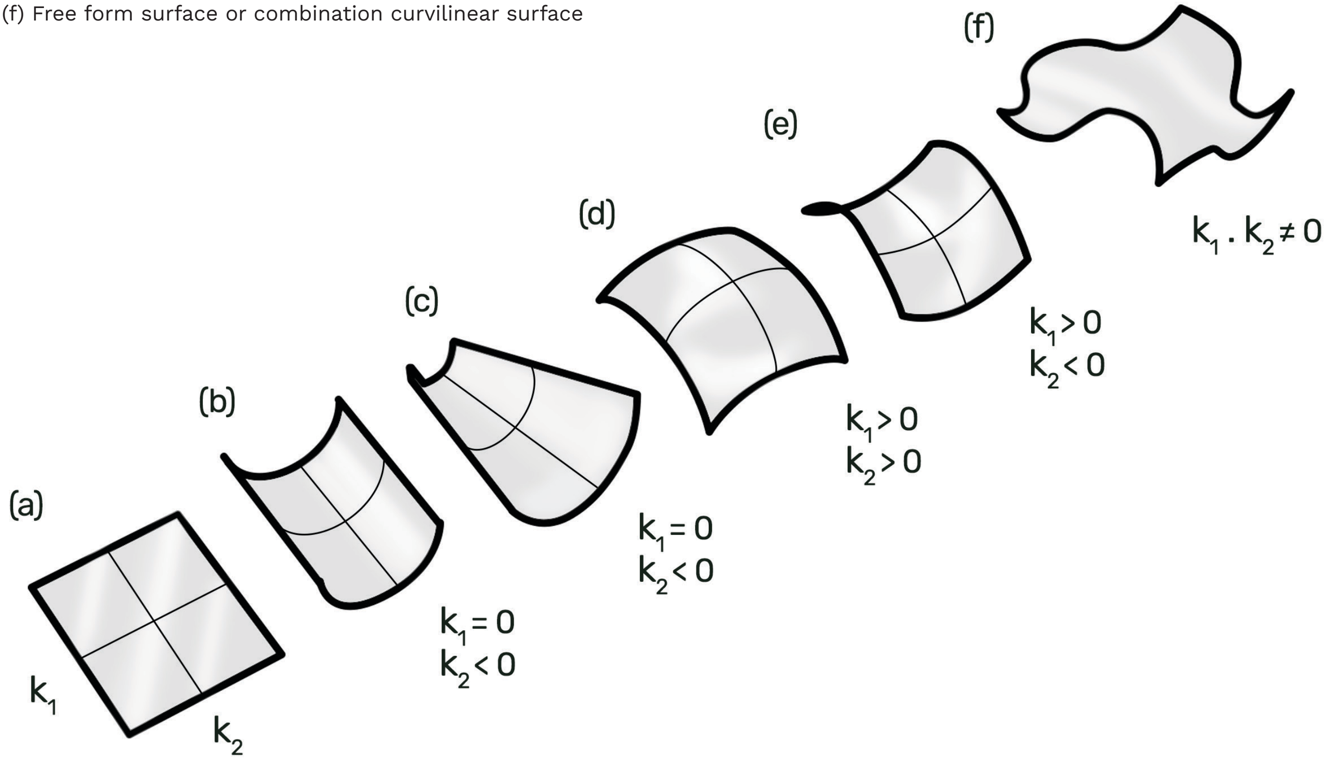


Illustration: **Own**
Gaussian Curve Notation: Adapted Correa et al., 2019

2.6

Developables & Non Developables

The single-curved panel represents one directional curvature or simple curvatures such as conical forms or cylindrical vaults. Both flat and single-curved surfaces are monoclastic as they possess zero Gaussian curvatures since the curvature in at least one direction is zero (Pronk & Dominicus, 2012 ; Correa et al., 2019).

The double-curved panel represents two or three directional curvatures in a panel, such as domes or saddle shapes, and thus are either anticlastic (+ve) or synclastic (-ve). (ibid.)

The free-form panel represents the contemporary yet complex combination of single and double curvatures, with ($K \neq 0$) in at least two directions and is a combination of anticlastic and synclastic along different axes (± ve).

Developable Curved Surfaces

(a) Planar flat surface
(b) Zero-curve bent or 'cylindrical'
(c) Zero-curve bent or 'conical'

Non-Developable Curved Surfaces

(e) Positive double-curved or 'dome-like'
(f) Negative double-curved or 'saddle-like'
(g) Free form or combination curvilinear surface

The nomenclature for surface geometries used in the review from now on:

1. Primary - Planar, Flat

2. Secondary - Singly Curved, Developable

3. Tertiary - Doubly Curved, Non-Developable, Free Form Surface

Classification

Across engineering practices, the 2D plane is a flat sheet of material used for panelling, as in ship-building and aerospace industries (Najjar, 2013). The flat sheet of material is the assumed point of reference for all fabrication approximations.

To understand why we are required to study the geometric behaviour of all surface types identified in Figure 1. The ability to transform into a 2D flat plane further differentiates the surface typology primarily into two mathematically identified classes, i.e. Developables and Non-Developables.

Developability

It directly implies the geometry's ability to be formed by folding a 2D plane's surface and transforming it back into 2-dimensional planes without any distortion or permanent changes.

For instance, raising two opposite sides of a flat sheet of paper creates a simple single curvature ($K = 0$) with no distortion, stretching, or tearing of the material.

All monoclastic surfaces with zero curvatures (see Figure 1: a, b, c), cylindrical or conical surfaces, can be made by folding a plane's surface without any degree of surface distortion.

In contrast, double-curved surfaces (see Figure 1: d, e, f) such as domes and saddles or freeform with ($K \neq 0$) cannot form out of flat sheets without stretching or tearing the material (Kalantar et al., 2016).

Therefore, all synclastic (positive curvatures) or anticlastic (negative curvatures) cannot transform into 2-dimensional planes without some degree of surface distortion (Correa et al., 2019).

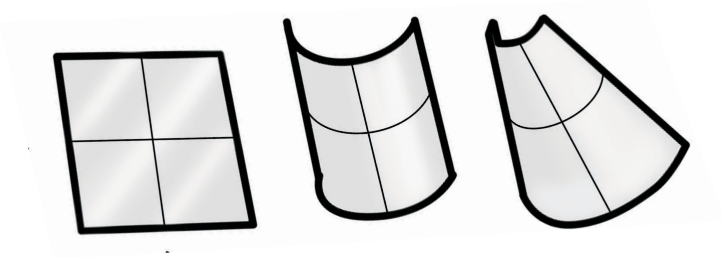


Fig: **Developable Surface Geometries**

- Planar flat surface
- Zero-curve bent surface or 'cylindrical' surface
- Zero-curve bent surface or 'conical' surface

2.7

Developable Panels

About **Developable Geometries**

In their paper titled Folded Developables, Duncan & Duncan (1982) identified surfaces widely used in engineering and briefly called 'developables'. They defined the developable surface as produced by curving a flat sheet so that deformation restricts to bending only. They proved that there is no mathematical extension in the sheet, and line lengths and preserved angles during deformation.

The surfaces with Gaussian curvatures of zero are easier to produce because they can be transformed or "developed" to the plane without any distortion, primarily planar and single-curved typologies. (Correa et al., 2019)

According to Duncan & Duncan (1982), many sheet materials, such as paper, plywood, and hardened sheet metals, could sustain bending without extension or shear. These materials are widely preferred for cladding in the conventional built environment, even half a century later.

Industrial **Revolution**

The transitions of cladding are relevant to analyse the relationship between geometry and material advancement for cladding.

The Industrial Revolution brought new building materials, iron, steel and glass, that rearranged the concept of function, size & form for architects.

Advancements in the 19th to 20th centuries saw enhanced machine tools and mechanised systems from traditional metal smithing. (Bowen et al., 2022). The advent of smith working being mechanised led to more metal working in buildings for ornamentation trends with faster production lines. (ibid.) Moving from stucco & bricks to cladding with metals and concrete, cladding protected the main structure with lighter materials yet complex designs.

2.7.1

Metallic Materials

Use of **Metal**

Today, the designs of numerous buildings with unique geometric cladding worldwide are such that the material constraints require high stiffness, strength and toughness as performance indicators.

Metal cladding predominantly bypasses concrete and glass/carbon composites in usage.
Metal cladding balances low-maintenance aesthetics and high operational performance during the use phase. Nevertheless, to explain the popularity of metals' association with developable geometries, the versatility of metals should be addressed further.

Metal Sheet forming is a widely preferred fabrication for metal cladding panels as sheet metal has a higher production run and less room for defects than cast metals (Lee & Kim, 2012). Due to their malleability, nearly all metals today can be easily machined with traditional metalworking instruments into different geometries during fabrication (Bowen et al., 2022).

Aluminium, for instance, is conventionally preferred in architectural skins due to its lustre, stability, durability and longer life in facade lifecycles, apart from being lightweight and easy to shape.

Metals like aluminium are 100% recyclable and widely cost-effective due to advanced industrial spread, thus increasing their popularity. Metals directly associated with the panelling of developable geometries can be conclusive for two reasons.

- The worldwide availability across regions of economic & climatic zones. (IEA, 2022)
- The standardisation of sheet forming fabrication for rolling and bending to form shapes and three-dimensionality over centuries. It is the most cost-effective sheet-forming technique for approximating complex surfaces today (Najjar, 2013).

2.7.2

Sheet Forming in Metals

Existing **Methods**

Modern manufacturing which use digital fabrication and design computing, require a wide variety of customized components. Only recently, very challenging and capital-intensive innovations emerged. The evolution in the production of sheet metal parts in the AEC sector - is extensively researched by Lee & Kim (2012).

Cutting, cold/hot roller-bending, and pressing are the general methods used to fabricate curved surfaces, along with unique methods such as hydroforming and multipoint forming.

There are many methods for fabricating curved surfaces like carving, casting, forging, drawing and extrusion for metal panel fabrication skin for complex facade geometry. These methods result in a high probability of surface defects and imperfections (Ock, 2021; ibid.)

The research by Lee & Kim (2012) shows no usage of a one-track particular processing method for a building. Several processing methods can often be optimized or combined to fabricate a panel of the desired shape.

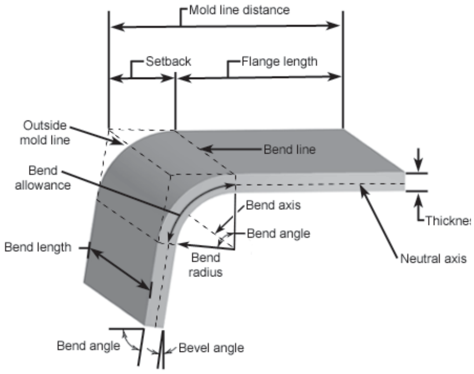
Roller / Press / Stretch Bending

Bending a material in one-way curves is the principal behind roller bending, press bending, or stretch bending, the most widely used methods.

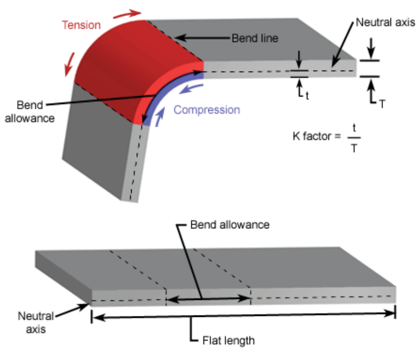
Roller bending (also known as roll bending or rolling) refers to pushing a material between a fixed roller and a curved surface-controlling roller to create a product with the desired curvature; this is the most general fabrication method used for one-way curved materials. In case of roller bending, the radius of a curved surface must be more than 200– 300 mm. If the radius is less than 200 mm, press bending is applicable. A press bending machine pushes and folds a sheet metal panel. Roller bending and press bending produce a uniformly bent shape.

Bending is classified as heat bending if heating accompanies the bending. Cold bending is an on-site practice, as it is cost-effective and workable at room temperature. Yielding curved surfaces by forcefully bending flat metal panels along the curvature at field temperature without heating is desirable to fabricators (Ock, 2021).

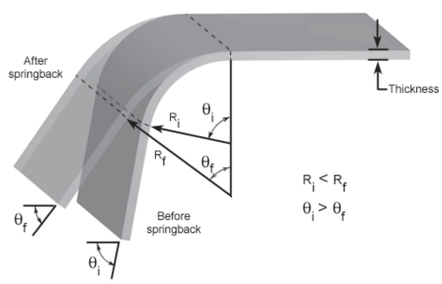
Bending Diagram



Neutral Axis Diagram



Elastic Spring Back Diagram



Source: Adapted Diagram on Sheet Metal Forming
https://www.custompartnet.com/wu/sheet-metal-forming

2.8

Non Developable Panels

About **Non Developable Geometries**

Complexity, as impressive as it might make a project can also be challenging to achieve in the built environment. As noted earlier in Section 2.6, Double-curved surfaces (see Figure below) such as domes and saddles or freeform with ($K \neq 0$) cannot form out of flat sheets without some degree of surface distortion (Correa et al., 2019) i.e., stretching or tearing the material (Kalantar et al., 2016).

A formal departure from basic normative geometries has established a broad research interest in material capacities and their progressive development. (Pantazis, 2019).

Despite the general perception, no technology currently exists for fabricating mass-customised, double-curved metal panels.

The survey by Lee & Kim (2012) found that forming non-developable, double-curved geometry using sheet metals employing existing processes is expensive and inefficient. Their study did develop a new multipoint stretch-forming method to fabricate the 45,133 unique panels required for the DDP in Seoul, South Korea. However, there are no cheaper ways to manufacture or mass-customise.

Developable **Approximation**

For the desired appearance of customised cladding on a free form structure, non-repetitive panels ought to be panelled and shape-formed in double curvature to meet the designed accuracy. Facade engineering links with standard geometry to segment or rationalise a freeform surface into simpler pieces for easy production (Pottmann, 2008).

Tabulating the possibilites, as reviewed:

Rationalising	Flat Panels	Single Curved Panels	Double Curved Panels
Flat Wall System	✓	✓	✓
Single Curved Wall System	Approximation by Triangulation	✓	—
Double Curved Wall System	Approximation by Triangulation	Approximation by Developable Strip Models	✓

Rationalization / **Optimization**

There are three implemented approaches to approximate free-form façade surfaces;

1. **Faceted Planar Panels**
   Approximation with flat panels will be incompetent to respect the curves of the wall system & may look choppy (Pottmann, 2008). However, an asymptotic curtain wall, as designed by the authors Schling & Wan (2022), can allow for planar flat panels to follow the curve. The geometry-based designed approach is distinctive and unexplored.

2. **Smooth Bent Strips**
   Singly curved panels will not be able to respect the curve of the wall system. However, a method that is less expensive than curving flat panels into double curved surfaces and is capable of better approximation than flat panels is segmentation into single curved panels through the developable strip model.

3. **Smaller Double-curved Panels**

The decision for a particular type of segmentation depends on aesthetics and budget. The visual appearance of a facade formed by triangulated surfaces differs from curved panels. Therefore, the approximate segmentation of a freeform shape into cost-effective single-curved panels is appealing (Pottmann, 2008); however, it still needs to be explored.

As building designs grow ambitious with complex geometries and scrutinized timelines, there is an increased dependency on engineering and fabrication partners for constructability, risk scenario and cost analysis in the earliest stages of conceptual design, as the expected scenario is of design feasibility without enduring multiple cycles of laborious—and expensive—design modifications.

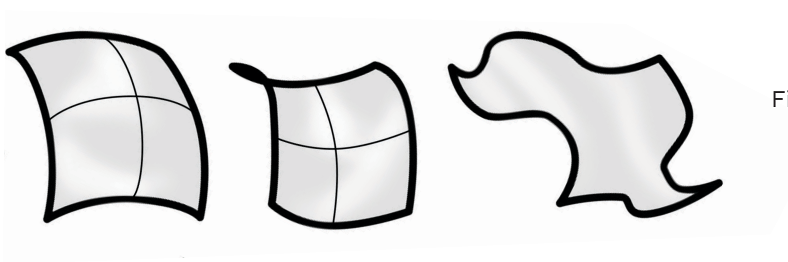


Fig: **Non - Developable Surface Geometries**

- Positive double-curved surface or 'dome-like' surface
- Negative double-curved surface or 'saddle-like' surface
- Free form surface or combination curvilinear surface

2.8.1

Composite Materials

As the non-developable panel is the most difficult to form, it displays significant quality discrepancy as compared to developable types, making free-form projects very complex overall and leading the contractors to turn to materials and production methods that ensure the as-built quality of the curved facade (Kavuma et al., 2019; Ock, 2021).

Hence synthetic composites were preferred as it meets the material parameters for the fabricators to deliver the design intent and avoid cost overruns. (Henriksen et al., 2015, ibid.)

About **Fibre Reinforced Composites**

Initially developed as a cladding material in the 1970s to 1980s, glass fibre reincforced composite was an ideal cladding material due to their durability, relatively lightweight, weather resistance and easy moldability into specific dimensions and shapes (Henriksen, Lo, & Knaack, 2016).

The composites have environmental impact compared to metals and offer higher built quality of curved facades, that is unachieved by sheet metal forming. Glass fibre-reinforced plastic has interchangeably replaced its concrete variants for cost and time considerations using conventional manufacturing methods.

Sprayed, premixed and automated premixed methods are the most common procedures for the production of GRC, as in several remarkable free-form buildings, including the Heydar Aliyev Cultural Center in Baku; the King Abdullah Petroleum Studies and Research Center in Riyadh, Saudi Arabia; the Foundation Louis Vuitton, in Paris; and the Qatar National Museum, in Doha. Among the three procedures for producing GRC, the sprayed method is the most flexible and feasible in achieving different shapes and offsets.

Forming **Methods of FRC's**

In the standard production of fibre-reinforced composites such as GFRC, a primary drawback is the necessity to manufacture moulds for creating suitably shaped panels, often employing CNC milling methods. CNC milling can create personalized forms using typical materials such as polystyrene foam, Styrofoam, wood, or metal can be used as the moulds depending on the strength required and cost.

2.8.2

Production Methodology

Feasibility **Challenges with Composites**

Capital-intensive projects can accommodate the mass production of diverse free-form panels with CNC-based shaping technologies.

However, small/midscale construction practices hired to deliver smaller batches of free-form panels to a project in a regional market mainly utilize traditional forming methods like sheet metal forming or mould-forming techniques. The conventional methods are more cost-effective and easier to access than the high-tech methods, but they cause discrepancies since the techniques greatly depend on the craftsmanship of panel fabricators.
(Buswell et al., 2007; Lee & Kim, 2012; Ock, 2021).

Multiple methods emerged over the years to produce double-curved elements. The most used mould techniques are static, reusable and flexible. A summary of the methods and their limits are in the following subsections.

Static **Moulding**

Timber formwork, involving the utilization of plywood or particle board, requires an elevated level of expertise for creating double-curved moulds. However, its static nature restricts the feasibility of manufacturing non-repetitive panels (Henriksen et al., 2015).

Steel formwork, predominantly employed in the precasting industry, facilitates mould reuse while maintaining the desired shape and surface quality. Nevertheless, its inherent rigidity and the substantial expense of in-situ casting discourage the production of unique panels (Henriksen et al., 2015).

Fig: **Timber Formwork** (Hayashi & Gondo, 2021)

Foam formwork, primarily employing EPS/XPS, can be efficiently shaped via CNC milling or wire cutting. Although cost-effective and recyclable, it falls short in the production of unique panelling (Ock, 2021; Henriksen et al., 2015). Fabric formwork, utilizing tensioned fabric to generate moulds, faces challenges in shape control due to fixed points, predominantly limiting its application to synclastic forms (Veenendaal et al., 2011).

Additive manufacturing, an evolving technique, obviates the necessity for moulds and permits the production of distinctive elements. However, this approach still grapples with the development of methodologies for printing double-curved reinforcement elements, and the cost-effectiveness hinges largely on project scale.

Fig: **Foam & Steel Formwork** (Ock, 2021)

Fig: **AM Formwork** (Vergara et al., 2017)

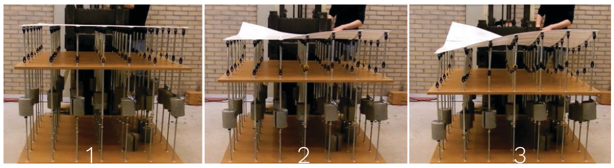
Flexible **Moulding**

For the production of free-form panels, flexible moulds (FM) are an alternative (Schipper, 2015; Henriksen, Lo & Knaack, 2016; Aşut, Eigenraam, & Christidi, 2018; Vergara et al., 2017) which allows for the singularity of each piece at no added cost.

The FM consists of a base plate with height adjustable actuators and a flexible layer which carries or forms the deformed mold. It is suitable for casting multiple double-curved non developable elements in the same setup. (Schipper & Eigenraam, 2015)

The performance of each panel starts with the configuration of the adjustable bed to obtain the desired shape, and then the GRC is poured/sprayed/printed onto it.

For the curing process, keeping the panel on the forming bed for at least a few hours is necessary, which slows down the procedure (Schipper et al., 2017).



Prototype of Kine-Mould (Schipper & Eigenraam, 2015)

Static Mould **Limitations**

The material waste and the intensive labour are significant drawbacks, making it challenging to produce, expensive, and time-consuming if the subtractive milling of a block of material brings no value addition to the manufacturing process (Pronk, Rooy, & Schinkel, 2009; Henriksen et al., 2015 ; Vergara et al., 2017; Ock, 2021).

The only drawback of conventional fibrous composites apart from its synthetic constituents, is the cost of the mould, especially in short or one-off series. “Since mould manufacturing often determines the cost of the panel, there are strong economic reasons to establish an innovative method that avoids the need for casting to reduce costs.” (Vergara et al., 2017, p.2)

Flexible Mould **Limitations**

Many issues concerning flexible moulds for free-form panels still need to be solved. There are several ways to optimise the Flexible Mould to manufacture more accurate moulds.

1. For example, settings must be digital, not manually adjusted (Aşut, Eigenraam, & Christidi, 2018; Spanolios, 2021).
2. Finish contour edges must be improved (Henriksen, Lo & Knaack, 2016).
3. The need for a feasible method for validating the geometry in order to predict the deformation of the flexible layer and, in doing so, prevent undesirable outcomes (Van Rijbroek et al., 2015).

2.8.3

Opportunities in Composite Sheet Forming

Alternative Forming Methods

Using composite materials in sheet forming applications had initially gained research interest through the automotive and aersopace industries, with research studies dating back to the 1970s up untill 2022.

On the face of it, structurally competent composites should be formable from a flat raw material blank to a complex shape, if following a suitable method (Tomas, 1997).

Various techniques like roll-forming, compression forming, machining were proven feasible with composites, with early investigations with unidirectional fibre composites (Hearle, 1967; Tucker, 1997) and a lesser extent on textile based reinforcement - woven & knitted fabrics.

The comprehensive research by Lim & Ramakrishna (1999, 2000, 2002) investigates the effects and mechanical behaviour of knitted fabric composites with techniques like deep drawing & stretchforming.

Therefore, thermoplastic composite sheet forming has been in research circles for decades, resulting in numerous forming techniques.

Composite **Sheet Forming**

Since forming a flat material into a curved component is conceptually identical to sheet metal forming, few thermoplastic composite sheet forming techniques borrow from the relatively matured field of metal forming (Tomas, 1997; Chanda & Bhattacharya, 2022)

Thermoplastic **Sheet Forming**

Metals can be exploited for their cold-bending plasticity and formable properties, similarly, sheet metal forming techniques are often applied to thermoplastic composite sheet forming, as thermoplastics, unlike thermosets have the ability to be reshaped with the controlled application of heat. (Bhattacharya, 1997; Tomas, 1997)

Almost all the standard manufacturing techniques for composite sheets, like match-die moulding, rubber-die moulding, hydro-forming, deep drawing, folding and roll forming, are adapted from sheet metal forming.

Missed **Opportunities**

The book Composite Sheet Forming by D. Bhattacharya (1997) had an article by Tomas (1997) in which the author reported that despite the technical feasibility of the mentioned processes, the widespread commercial success of thermoplastic sheet forming techniques was rare, but the article reported an optimistic projection.

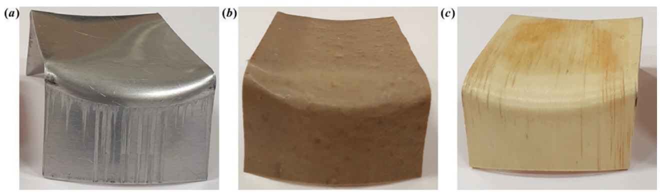
This trend was fact-checked and corroborated by the latest research from Bhattacharya and Chanda (2022), that **despite existing investigations on composite sheet-forming, complex structures using developable surfaces on fibrous composite materials still need to be reported.**

Potential with Facade Cladding

Sheet forming is the **most mature process** used in **metal forming (**D. Bhattacharya, 1997) and has the **infrastructural potency t**o adapt or modify to suit the needs of **forming composite sheets.**

At the same time, modification and redesigning composites to respond and comply with existing sheet-forming methods can lead to an entirely new approach in composite sheet forming for facade panel manufacturing.

With extensive studies on the mechanical competence of organic fibre architectures and the advent of biobased options for thermoplastic matrices, the scope of engineered biocomposites is beyond the traditional applications of aircraft and automobiles & has immense potential in the building industry.



Formed Developables
(Chanda & Bhattacharya, 2022)
(L-R) Metal, Flax PP Sheet, Plywood

2.9

Circularity Gap

Call to **Action**

As estabilished, it is predictable that optimizing composites is increasingly adopted, with AEC industry as the largest consumer holding a 37 % market share. (EuCia, 2022)

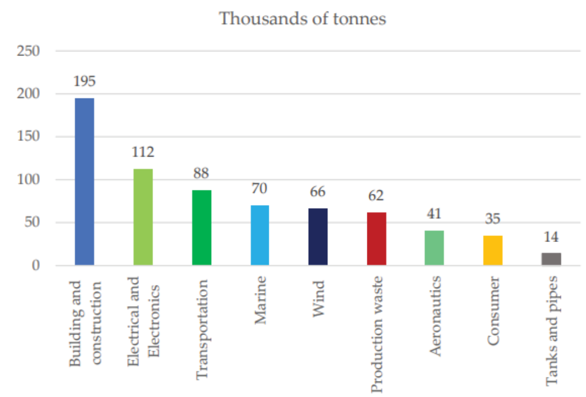
More than 90 % of all FRP's produced were GFRP as the material properties allows custom engineering to for adaptive mouldability and constituent flexibility in complex profiles. (Joustra, Flipsen & Balkenende, 2021). GFRP allows the components to be lightweight with high strength, they further reduce material usage in mass-centric applications like facade cladding and components.

However, the benefits of GFRP over Aluminium during the use phase in a facade do not match the impacts due to the lifecycle of composite products. More than 75% of the produced GFRP use thermoset resin, disallowing thermoforming or reusability.

Typical recycling processes are hardly viable economically as they severely degrade materials & tend to break down the composites into constituents, thus losing the specific material properties of GFRP.

As a consequence, at the end of a lifecycle, 98% GFRP waste is landfilled or incinerated with only 2% recycled, as per a 2006 report by Halliwell. The CAGR of FRP is 9% today, along with 12.1 Mil. Tons Produced in 2021 (EuCia 2022), with each ton of glass fibre producing 2.5 T CO_2 (Qureshi, 2022).

Below is a table adapted by Qureshi (2022) extensive research that predicts the estimated FRP waste production in 2025 by the Building and Construction Industry is to be 195,000 tonnes.



1/3rd of FRP production accounts for waste generation and as per EuCia (2022), EU alone produced 301 KiloTonnes of FRP in 2020. All statistics of GFRP indicate the impending loss of material value, and zero reuse potential and accelerating the depletion resources for indirect waste generation.

Biobased Composites **- Review**

The rising environmental consciousness has encouraged efforts to configure novel biobased alternatives to conventional non-renewable, synthetic(glass/carbon) fibre-reinforced composites for diverse end-use applications (Andrew & Dhakal, 2022).

The emerging Natural Fibre Reinforced Polymeric composites display competent mechanical properties as compared to the glass fibre opponent. NFRP's belong to renewable origins for the fibre architecture & matrix materials and are capable of partial biodegradation along with low-carbon & carbon storing properties.

Despite studies on composite sheet-forming & competence of organic fibre architectures, the formability of fibrous biocomposites for complex structures is underexplored.

Academic research is widely available, but commercial FRP products using natural fibres – do not exist yet. (Fiore et al., 2015; Mugahed Amran et al. 2018; Vinay et al. 2022; Qureshi, 2022)

Biocomposites have a higher circularity potential employing smart manufacturing as they reduce the use of glass/synthetic fibre, however their overall circularity potential as in the scale of facade products is undetermined.

2.10

Identified Research Gap

Metal Cladding **Drawbacks**

The global aluminium sector was directly responsible for 275 Metric Tonnes of CO2 emissions in 2021: a 2% increase from 2020 due to production levelling off globally in 2019-20) & if indirect emissions included electricity consumption, the total is 1.1 Giga Tonnes of CO2 (IEA, 2022). The demand for aluminium will continue growing, in all likelihood, due to the rising population and global GDP.

Metals like aluminium are still paramount to the built environment's facade industry, as the building sector contributes to 1.5 % of total CO2 emissions from Aluminium (Architecture 2030, 2022).

Sheet metal forming is a preferred technology to form and shape products across the aerospace, automotive, and apparatus industries but mainly in the AEC industry, favouring all industrial production sectors (Trzepieciński, 2020). The advantages of metal forming consist of (i) high productivity, (ii) low costs per part, and (iii) minimum scrap material and energy consumption. However, every process has advantages and disadvantages, while some are extremely expensive, and others can only produce panels smaller than a specific size.

Thus, it is essential to conclude that existing sheet metal processing limitations, especially for non-developable geometries or doubly curved panels led to the advancement of non-metal materials like engineered composites with formwork-based fabrication.

Composite Cladding **Drawbacks**

Synthetic composites like GFRP are durable, stable, lightweight, and strong as metals. They are continually rising in production, with synthetic glass fibres used in 95% of all fibre-reinforced composites, with more than 1.141 million tons produced across Europe (Witten & Mathes, 2022).

Arguably, all complex facades using GFRP and similar synthetic composites are yet to be cycled in closed resource and energy loops. The high-value material will be disposed of & landfilled in unsustainable ways, as seen with GFRP blades from wind energy plants built 20 years ago, meeting their end of life in the coming years & creating tonnes of highly non-reusable/recyclable waste. Until a globally applicable lifecycle strategy is found, facade cladding systems with synthetic fibre composites lack reusability, second-life potential or even sustainable downcycling thus encouraging efforts in biocomposites as an alternative.

The Research **Gap**

The novel introduction of developable geometries in engineered biocomposites for their enhanced use, backed by circular design strategies to close the resource loop for composite materials, is underexplored in facade cladding practice & literature.

This review will close the gap to pioneer scientific relevance for further innovation with circular intents.

Fig 5: **The Construction Material Pyramid**, Class of Metals

Source: https://www.materialepyramiden.dk/

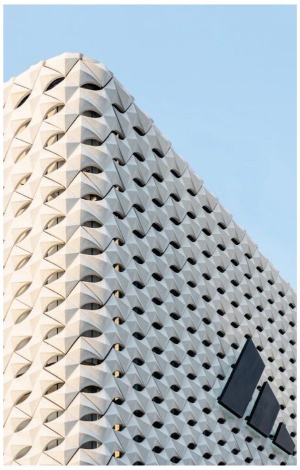


Fig 6: GFRC Facade for Adidas, 2021 Shenzhen, China

Source: DUO Photography (2021)

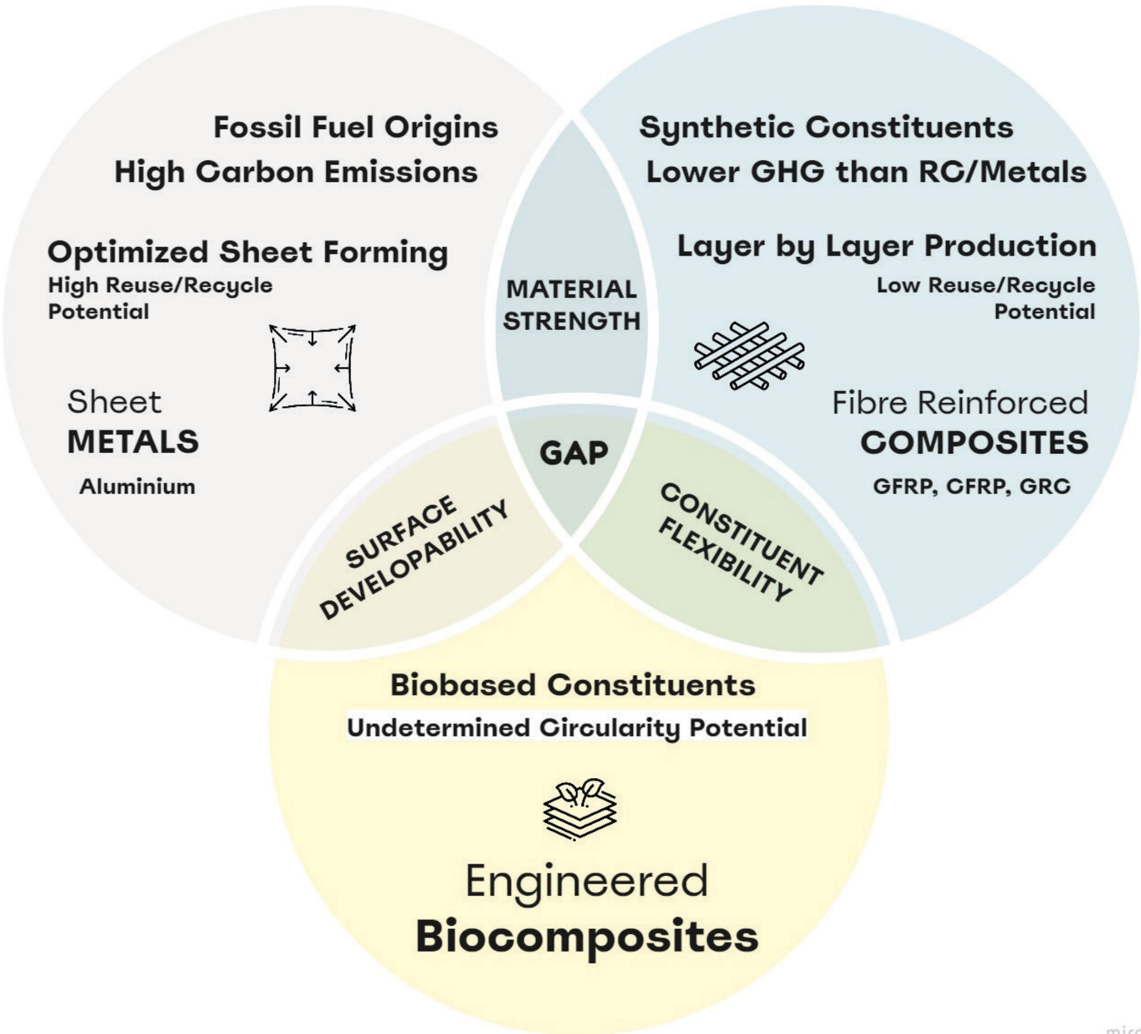
Fig 7: GFRC Blades buried in landfill, 2020 Wyoming, USA

Source: Benjamin Rasmussen (2020)

2.11

Empirical Knowledge Gap

The empirical performance of natural fibre-reinforced biocomposites in complex geometries is yet to be researched in detail. The circularity potential of these biocomposites and the corresponding limits of functionality as a panel in building envelopes, will be a part of this evaluation.



Suppose the developability of fibrous biocomposites is empirically proven/validated through Sheet Metal Forming or through modifying Composite Sheet Forming. In that case, the research outcomes will pioneer innovation for engineered biocomposites to compete with the reuse potential, formability and competence of metals like Aluminium, with flexibility in constituent engineering like GFRC, additionally demonstrating circular design strategies as a possibility for products with fibre-reinforced composites.

If addressed, this design-research gap can reduce stakeholders' resistance to switching to composites and lead us to our desired geometries through existing infrastructure and circular design strategies without altering the natural ecosystems with high GHG emissions, generating technical waste streams or exhausting resources.

2.12

Circular Product Strategies- A Review

Product **Chain Circularity**

This research focuses on the product level, encompassing the scales of materials and components.

A 'product chain' tracks all stages of a product, from extracting resources to discarding the product and its parts after use. Potting et al. (2017) notes that in an idealistic circular economy, the materials reclaimed from a discarded product would retain their original quality to be applied to a similar product.

However, realistic recovery often demands excessive energy to counter the reduced quality and pollution caused due to the mixing of materials. Materials recovered from discarded products (secondary materials) cannot be applied again for the same product & quality but often find application in lower-grade products.

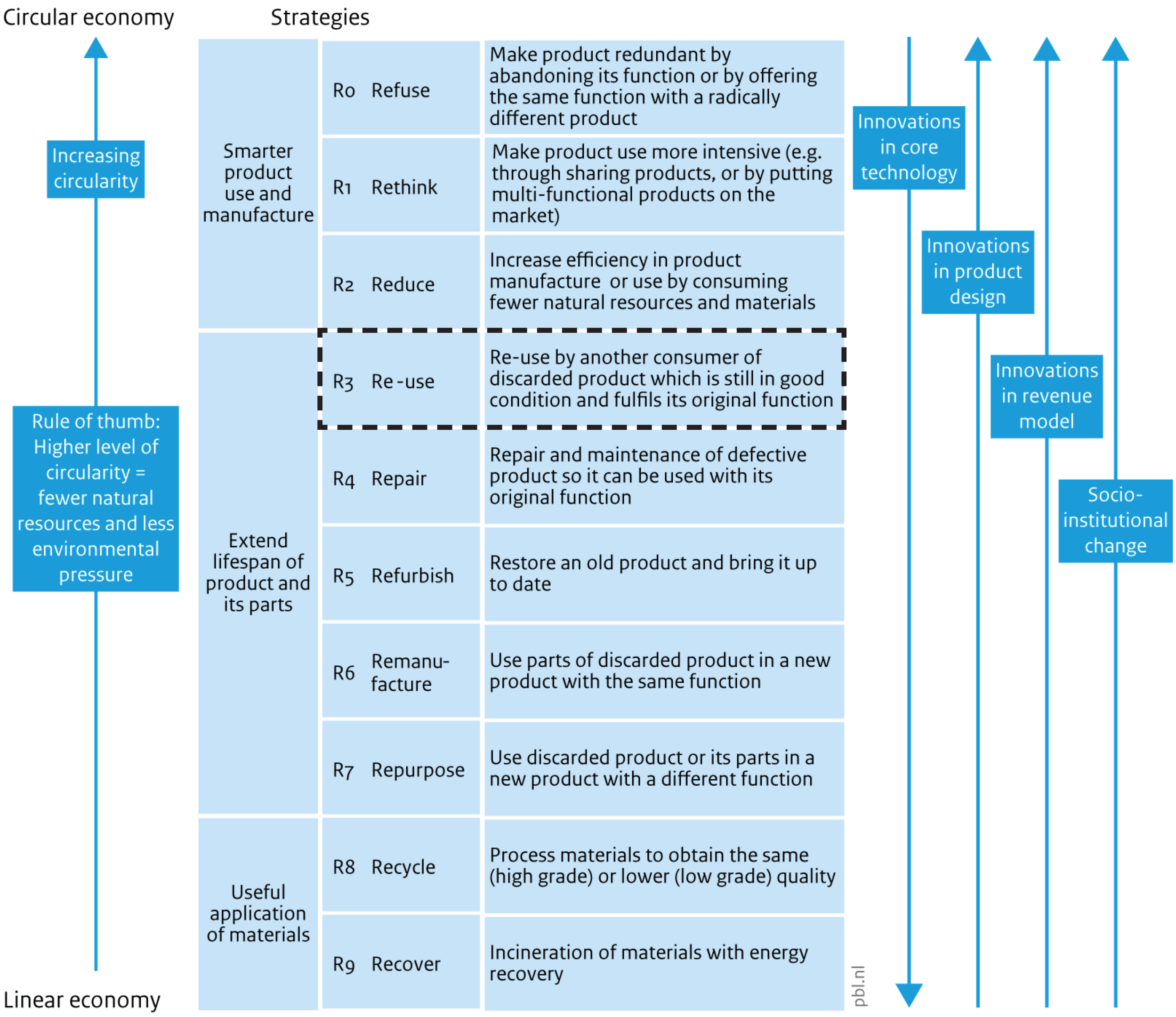
Thus, a material chain can be longer than a single 'product chain'.

The 'ultimate circularity' is achieved when a product chain is closed due to the materials being applied and used repeatedly at the same value.

The ideal situation is where no additional resources are needed to produce materials required for the product, and discarded products can be structurally reused, so no waste is generated. Potting et al. (2017) report that 'ultimate circularity' is yet to be feasible in real-world practice.

However, it is critical to this research to enquire about the limits and prospects of circularity in a functional facade product made of the proposed material, i.e. natural fibre-reinforced polymers.

Circularity strategies within the production chain, in order of priority



Circularity strategies are ordered for priority according to their rank of circularity.
As a rule of thumb, more circularity equals more environmental benefits.

A higher level of circularity of materials in a product chain means that those materials remain in the chain for a more extended period. It can be applied again after a product is discarded, preferably retaining its original quality. As a result, fewer natural resources are needed to produce new materials for manufacturing products and their subsequent use.

Smart manufacturing & use has the highest priority as avoiding resource extraction and production of materials benefit the environment. Lifetime extension and recycling materials are strategies that follow behind. Energy recovery from incineration has the lowest priority as a circular strategy because the materials lose value and applicability.

The 10R framework (Cramer, 2017): Refuse, Reduce, Renew, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover, presents a nuanced waste hierarchy framework, originates mainly from the field of product design. The 10R model cannot be built as a framework but relies on transformation and adaption in design practice. Thus, a crucial question for building design is how to translate this framework into building design practices.

Circular Product **Design Framework**

Joustra & Bessai (2021) have devised a design guide for products containing composite materials in a circular economy, after their research.

The five strategies out of which three are discussed and the associated design aspects each help to enable different circular strategies for composite products, thus maximizing value within the system. Circular strategies describe measures to preserve product or material integrity, i.e., remanufacturing or recycling, and have a strong connection to business models. Design aspects relate to product realisation and provide insights as to how recovery can be anticipated by design intent, such as choices with respect to materials and connections. The framework shows how these are connected.

Circular Design Strategy I Joustra & Bessai (2021)

Lifetime Extension

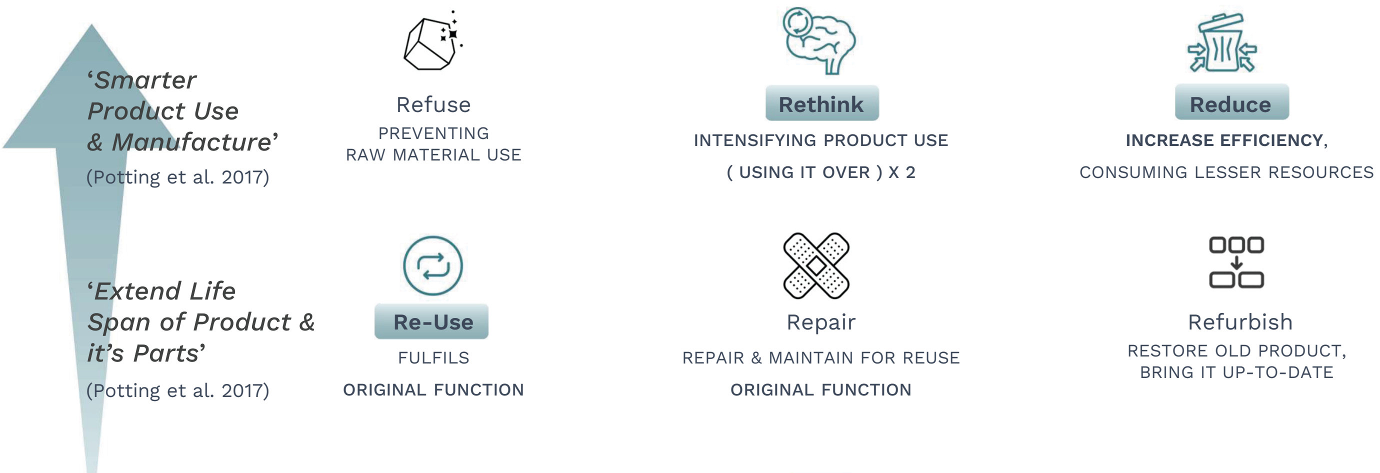
Lifetime extension concerns all interventions taken during the product lifetime to prolong its use phase. This is done through maintenance, repair, upgrades and adaptations. The opportunities for lifetime extension depend on the product design & operational context.

Product Recovery

to increase the number of use cycles through refurbishment and remanufacturing of products. It also includes harvesting parts to reuse them as spares for lifetime extension measures

Structural Reuse

Structural reuse takes place through repurposing, resizing, or reshaping the product, preserving the material integrity by reusing the material as-is.
These actions discard the original product function, but maintain the unique structural properties, defined by the combination of material composition and structural design. Thermoplastic matrix composites can be remoulded into new products.



Summary

The second chapter thoroughly overviews facade cladding systems in building construction, focusing on design, functionality, materials, manufacturing, and surface typology.

It delves into the complexities of panel geometries, fabrication methods, and the challenges that arise with different surfaces and materials. This extensive exploration reveals the inherent interdependence of materials and manufacturing, emphasizing how choices in these areas impact cost and feasibility.

The narrative shifts from traditional metal cladding systems, analyzing their limitations and environmental drawbacks, to alternative materials like fibrous biocomposites that could offer circularity potential and reduced ecological impacts.

The chapter underscores the potential of flexible moulds in creating free-form panels while acknowledging their limitations, such as the need for digital adjustments and optimized geometry validation.

The discussion extends to the underexplored potential of developable geometries in engineered biocomposites for facade cladding, pinpointing a research gap ripe for scientific innovation.

In all, the chapter advocates for the pursuit of innovative, environmentally-friendly alternatives to conventional cladding materials and methods.

These breakthroughs could reconcile the formability and reuse potential of metals with the sustainability and circular design strategies of biocomposites, thus revolutionizing facade cladding systems.

03

material study literature **review**

This chapter will review the literature on **natural fibre reinforcement** and **biobased matrix** constituents, & recommend a **suitable circularity strategy** for the engineered biocomposite.

This section will rationalize **constituents**, **sequencing**, **consolidation** & **material data** to engineer a **biocomposite** fit for **façade** panel.

3.1

Natural Fibre Composites

Sustainable **Development**

Pursuing sustainable development requires a systems approach in materials, design, manufacturing and management.

In this viewpoint, the built environment will continue to require solutions driven by lighter-weight, energy-efficient, renewable and carbon-sequestering building materials in the age of progressing economies spending on rapid urbanisation. (Väisänen et al. 2017; Stokke et al. 2014; Fiksel, 2003).

Research from past decades has presented significant enhancements in Fibre-reinforced polymers (FRP) composites to succeed as an alternative over traditional high-emission materials with a broader spectrum of material functionality.

Natural **Alternatives**

However, their fossil-fuel origins and non-recyclable end caused ecological concerns. This concern compelled researchers and governmental policies to align in seeking notable development with 'green alternatives' via biocomposites. (Rajak et al., 2019; Väisänen et al. 2017; Dahy, 2019).

Replacing lignocellulosic natural fibres (NF) in place of synthetic fibres (carbon and glass) offers natural fibre-reinforced polymers (NFRP) or biocomposites that serve as an advanced carbon-sink solution with essential functions & properties throu`gh abundant & annually renewable biomasses (Dahy, 2019; Väisänen et al., 2017).

Future **Prospects**

In 2016, the biocomposite market saw a valuation of USD 4.46 billion, with the construction industry accounting for the highest usage at 56.0%.

A recent study on Natural Fibre Composites noted steady progress despite Covid-19, aligning with the 11.8% CAGR from 2016 -2024. In 2022, the global market recorded 3,738.76 kilotons of NFC, and the AEC sector can lead the demand till 2030, as biocomposites offer a vital building material for the future (Gurunathan et al., 2015; Dahy, 2019; Research and Market NFC Report, 2022).

Major **Drivers**

The fabrication from biobased feedstock is likely to rise from 12% in 2010 to ~25% in 2030 (Andrew & Dhakal, 2022) owing to significant drivers of demand for natural fibres such as (Faruk et al., 2013; Kerni et al., 2020):

a) abundant & renewable raw material source (mostly agro-waste based)

b) high impact resistance, high flexibility, low specific gravity,

c) less abrasiveness to equipment, fewer health hazards

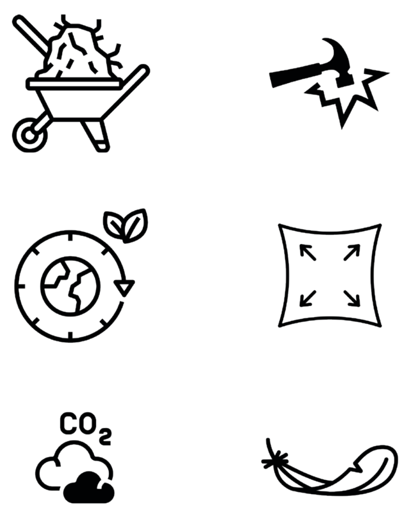
d) lower density, lower energy consumption and GHG emissions

e) lower costs than synthetic fibres, with lesser fuel consumption during processing

f) local fibres are independent of economic volatility and global oil prices

g) governmental policy support to advance products with biomasses

In a nutshell, the differentiators of biocomposites over the E-glass counterparts are — comparatively high specific mechanical properties, thermal insulation, CO_2 neutrality, good damping properties, high health safety, good fatigue, abrasive and corrosion resistance, availability, high acoustic insulation, low density, less production energy and lightweight-ness. (Andrew & Dhakal, 2021)



3.2

Natural Fibre Polymeric Composites

Classification: **NFPC**

Fundamentally, natural fibre-reinforced polymers as composites are multiphase materials with two principal components classified as, i.e. base material (matrix) & filler material (reinforcement).

The base material is called the matrix, and it binds the filler material, which delivers reinforcement in the forms of sheets, fragments, particles or fibres. (Rajak et al., 2019; Kerni et al., 2020)

Thus, NFRP lends the biocomposite status by natural fibres embedded as the reinforcement (filler) in a polymer matrix (base), which may also be of biological origin. (Vaisanen et al., 2016, Kerni et al., 2020)

Furthermore, the natural reinforcement fibres are the primary load-bearing constituent in the composite as the polymer matrix constituent surrounds the reinforcement for protection & support.
Therefore, variables like typology, arrangement, volume and production method can directly influence the NFRP.

Reinforcement **System**

Natural Fibre Origins

Origins of annually renewable biomasses are primarily plant-based lignocellulosic fibres derived either directly from agricultural sources (primary plants grown for their fibre content) or as processing or production residues (secondary plants from which fibres are the byproducts) when crops are processed for their primary uses. (Bassyouni et al.,2015; Kerni et al., 2020).

Lignocellulosic fibres have attracted significant focus & higher application potential across industries like automotive, industrial products & the built environment.

In practice, extracting natural lignocellulosic fibres can offer direct socio-economic benefits in rural societies, particularly in less developed regions with ample materials.

In addition, their capability as reinforcing materials in several matrices is owing to favourable characteristics such as low costs, biodegradability, accessibility, and competent physical and mechanical properties. (Andrew & Dhakal, 2021; Rajak et al., 2019)

Fibre **Typology**

Various natural fibres are known as reinforcement in generating natural fibre-reinforced polymer composites. Their categorisation is based on their origin source:

a) Stalk Fibres: Wheat, Corn and Rice.

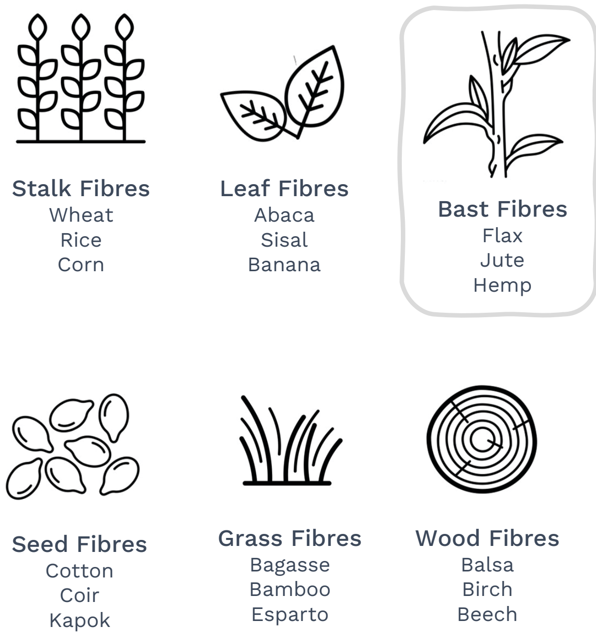
b) Leaf Fibres: Abaca, Sisal and Pineapple

c) **Bast Fibres:** Jute, Flax, Hemp, Ramie and Kenaf

d) Seed Fibres: Coir, Cotton and Kapok

e) Grass Fibres: Bagasse, Bamboo, Esparto

f) Wood Fibres: Balsa, Birch, Beech



> "bast fibres have exceptional strength"

(Llyod, 1996; Mohanty et al., 2005)

3.3

Fibre Architecture

Fibre **Structure**

The intended application is to develop a biocomposite for facade components, and fibrous reinforcements can be manufactured & customised for end-use potential, as noted by Libo Yan & the authors (2011).

We shall address natural fibre architecture and corresponding structural integrity to understand the difference in configurations and their influence on composites.

Classification

In some studies, the arrangement of fibres in the composite, also called configurations, has the most considerable influence on the composite behaviour.

Based on structural integrity, fibre linearity and continuity, Fibre architecture is classified into four groups: discrete, continuous, planar interlaced (2D) and fully integrated (3D) structures (Chou & Ko, 1989).

Different fibre architectures can be classified based on arrangement (Todor et al., 2022):

- **unidirectional:** consisting of fibres oriented in a specific direction in space, arranged one-way;
- **bidirectional:** consisting of fibres, facing surfaces, arranged bidirectionally (woven type);
- **tridirectional:** consisting of multi-direction fibres with the spatial arrangement (volume braiding);

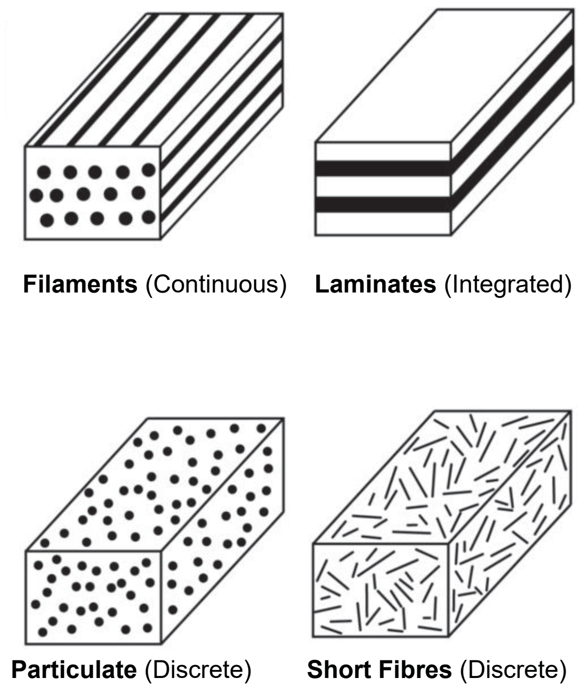
The geometric arrangement, such as continuous, randomly oriented or woven fabric, heavily influences the mechanical properties of the resultant composites (Aisyah et al., 2021).

Therefore, the arrangement can be chosen according to the mechanical characteristics and conditions of the use/application.

Favoured **Architecture**

Out of all arrangements, fabrics are widely preferred as reinforcements due to the high level of conformability for composite applications.

The interlocking characteristics of a woven reinforcement system allow excellent integrity and higher strength than fibre matrix adhesion. (Alavudeen et al., 2015).



Level	Reinforcement	Architecture	Arrangement	Orientation	Entanglement
I	Discrete	Chopped Fibres	Discontinuous	Uncontrolled	None
II	Linear	Filaments	Continuous	Linear	None
III	Laminar	Simple Fabric	Continuous	Planar	Planar
IV	Integrated	Advanced Fabric	Continuous	3-D	3-D

Fig : Examples illustrated above (Scardino, 1989)

Fig : **Constructive Classification of Fibre Architecture as seen in Composites**

(Table Adapted from Hu, 2008; Ciobanu, 2011 as per notes from Chou & Ko, 1989)

3.4

Woven Reinforced Composites

Woven / **Textile Reinforced**

Woven composites, called textile-reinforced composites, use technical textiles to produce near-net-shape preforms with high stability.
In addition, using a woven technique presents high density, specific strength, dimensional stability & improved fatigue life (Ciobanu, 2011)—the versatile woven reinforcement is in a broad spectrum of consumer goods due to excellent formability. (Aisyah et al., 2021; Alavudeen et al., 2014)

Controlled Anisotropy
The main advantage of woven architecture is the possibility of pre-directing the filaments in the intended direction, influencing the final properties.
'Controlled anisotropy' means controlling the fibre placement in preferential directions according to the maximum strain. (Ciobanu, 2011; Aisyah et al., 2021).

Weaving Techniques
Aisyah et al. (2021) extensively noted that the technique of weaving to produce fabrics had received widespread attention for its flexibility & high productivity to produce diverse weaves (fabric configurations — plain/cross-stitch/twill/satin) and superior mechanical properties than those obtained using techniques like knitting, braiding or stitching.
Weaving involves typical pattern interlacing of the warp yarns(fibres) that run along the length and weft yarns(fibres) that run perpendicular to the warp yarns, crossing using a loom.

Structure of **Fabrics**

Textile pre-forming methods are a large family of techniques used to create structures for composite materials (Chou, 1989). The ideal textile pre-form depends on the specific needs of the process and the final product.

Below are key features to consider when choosing a textile pre-form:

a) the ability to reinforce in multiple directions within a plane,

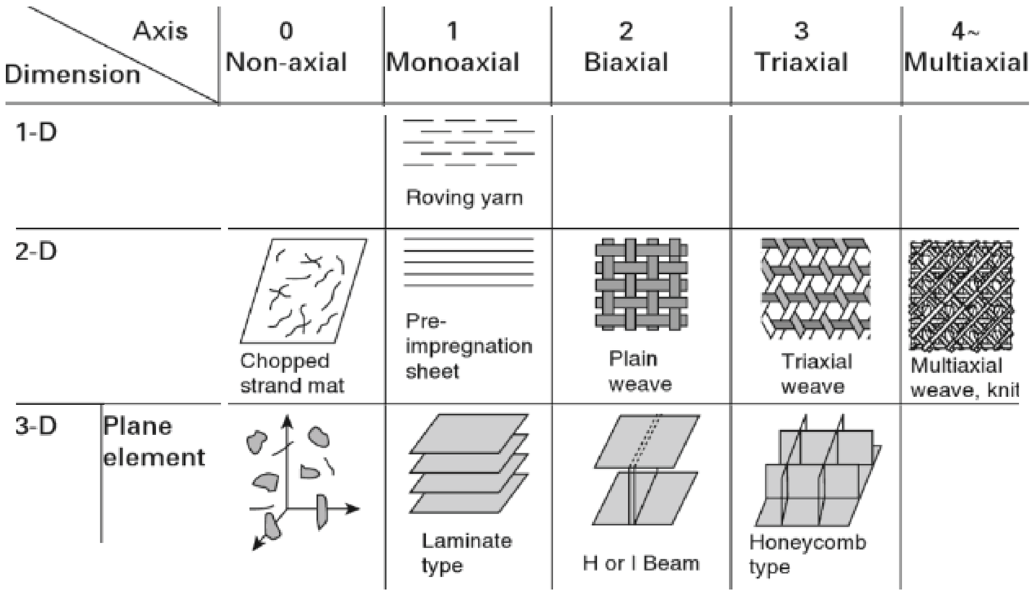
b) to reinforce through the thickness,

c) to create a specific shape during manufacturing

There are numerous ways to classify textile reinforcement structures based on the pre-forms characteristics. One way is to look at the arrangement of fibres or yarns and the overall geometry.

Fukuta and his team (1986) based their classification system (Figure below) on various factors, such as the fibre/yarn direction, the number of yarns, and the dimension of the structure, to categorise textile structures.

These can range from non-axial to multiaxial systems, where yarns are introduced from four or more directions.



Other factors in their classification system include the dimension (1D, 2D, or 3D), the direction of reinforcement, fibre continuity, linearity of reinforcement, bundle size, the twist of the fibre bundle, integration of structure, manufacturing method, and packing density (Badawi, 2008; Hu, 2008; Wang et al., 2017).

3.5

Polymer Matrix Systems

Matrix **Importance**

The fibrous reinforcement system carries most of the structural loads, thus providing macroscopic stiffness and strength.

However, the matrix system dominates the composite's shape, surface appearance, environmental tolerance, and overall durability.

Composite **Types**

Three types of embedded matrix composites exist; MMCs (metal matrix composites), PMCs and CMCs (ceramic matrix composites).

It should be appreciated that the most significant proportion of composites in industrial use is polymeric composites. (Clyne & Hull, 2019). Most commercial composites use a polymer matrix due to low costs and ease of manufacturing (Aisyah, 2021).

This study forwards on Polymer Matrix Composites (PMCs), which offer the broadest and most varied range of use and current industrial significance (Clyne & Hull, 2019; Todor et al., 2022).

PMC **Focus**

Using natural fibres in PMCs has the potential to create biocomposites with improved mechanical properties, making them suited for a broader range of applications.

A growing interest is in developing PMCs with natural fibre reinforcements to create high-performance and sustainable biocomposites. However, the non-biodegradability of polymers contributes to severe environmental issues. (Aisyah, 2021)

Matrix **Origins**

In recent times, numerous research studies have investigated the usage of renewable and sustainable matrices for composite material production (green composites) by combining biodegradable polymer matrices with fibres (Faruk et al., 2014; Andrew & Dhakal, 2022; Yıldızhan et al., 2018).

Andrew & Dhakal (2022) review the state-of-the-art matrices for polymeric composites (see Figure 1).
They note that, based on synthesis methodology, except for the polymers originating from fossils, most originated from sustainable biomass.

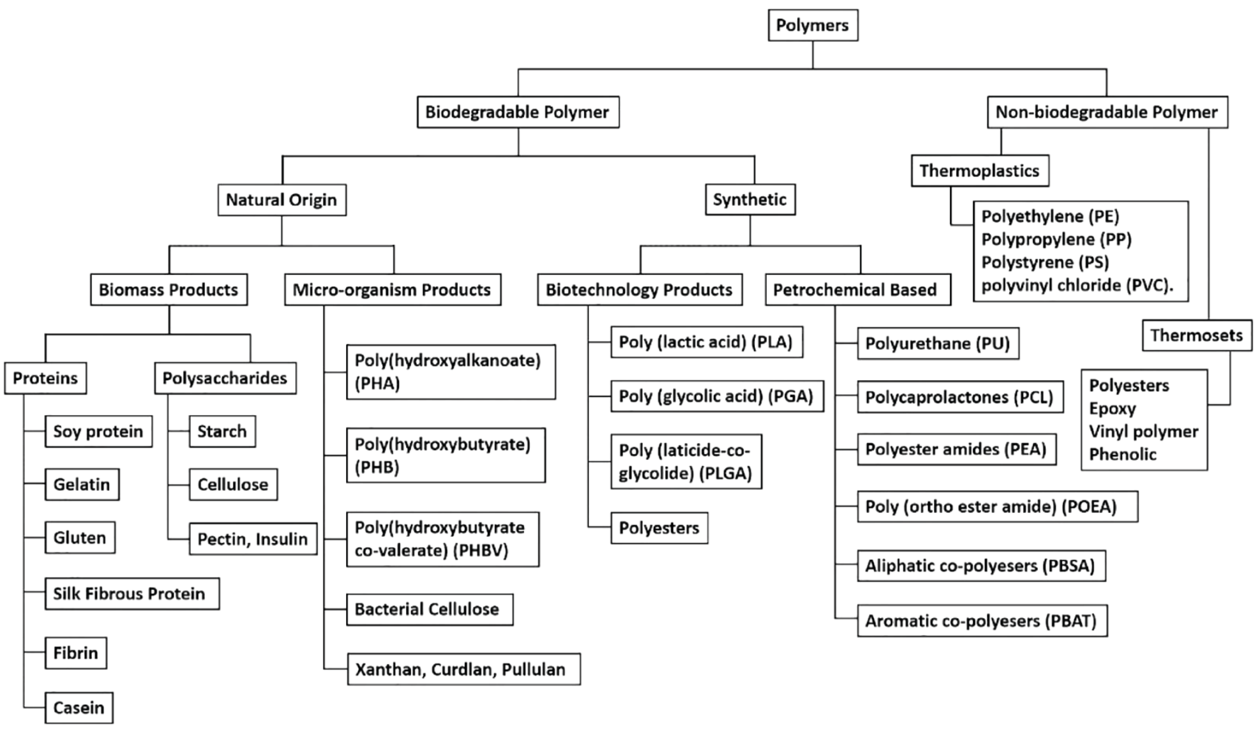


Fig: **Polymer Classification** (Andrew & Dhakal, 2022)

NFPC **Characteristics**

The partial substitution of the polymer with natural fibres provides multiple advantages as polymers are most common, inexpensive and typically have low density. In addition, polymers are easy to process, offer good mechanical properties and generally provide good adhesion.

Due to the low processing temperatures of polymers, many organic reinforcements are prevalent. Some of the earliest composites were fibre, cloth, and pitch layers. (Vaisanen et al., 2017; Clyne & Hull, 2019)

More importantly, NFRPCs show better performance in life cycle assessments (LCA) (Joshi et al., 2004) and structural assessments of tensile strength and elastic modulus when compared to conventionally reinforced composites (Mohanty et al., 2006; Vaisanen et al., 2017).

Thermo **- Sets/Plastics**

Categorising NFPCs into complete (bio-based) or partial biocomposites (petroleum-based) based on the selected polymer matrix based on their origin.

A typical polymeric matrix can be either viscoelastic or viscoplastic, implying it is affected by time, temperature & moisture.

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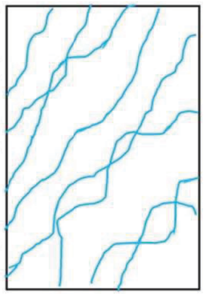
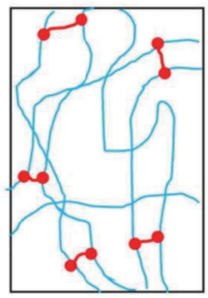
Thermoset and thermoplastic are terms used to identify polymers & their behaviour broadly. (Vaisanen et al., 2017; Clyne & Hull, 2019)

Thermo-***Plastics***



Thermoplastic matrix has polymer chains in contact, which are not cross-linked. A thermoplastic can be remoulded to a new shape when heated to approximately the forming temperature.
Such plastics are Polypropylene (PP), polyethene (PE), polystyrene (PS) and polyvinyl chloride (PVC)

Thermo-***Sets***



Thermoset matrix have cross-linked polymer chains, meaning a thermoset creates an irreversible bond and cannot remould after curing. Thermoset matrices are sometimes formed at higher temperatures for composite applications (Clyne & Hull, 2019). Phenolic, polyester (PE), and epoxy resins are the commonly used thermosets.

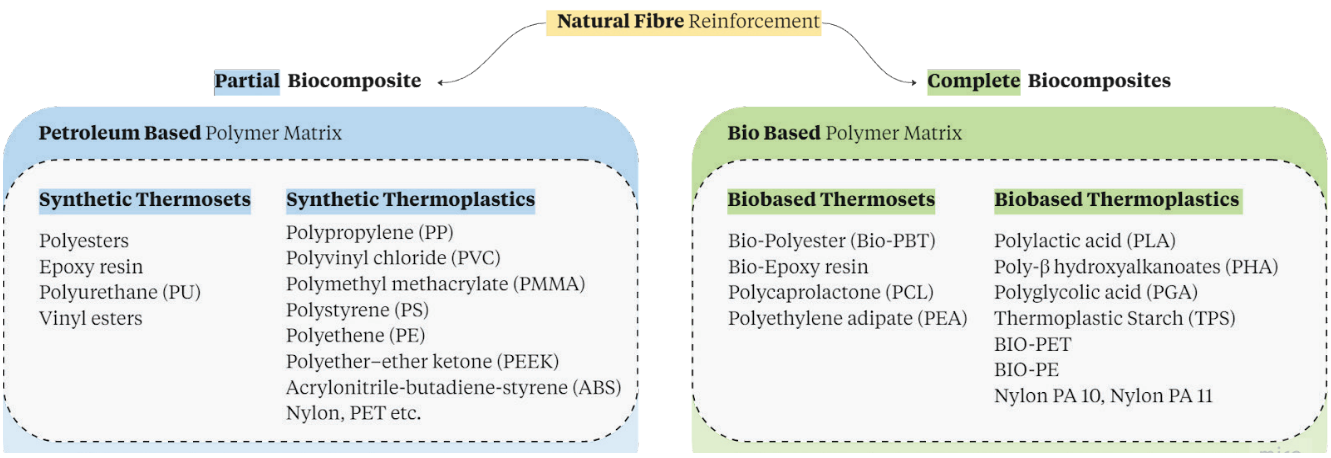
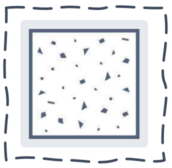


Fig: **Widely Used Matrix - NFPCs** (Faruk et al., 2012; Vaisanen et al., 2017; Andrew & Dhakal, 2022)

3.6

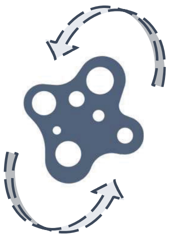
Gap Analysis

Thermosets **Challenge**



Joustra & Bessai (2021) highlight that most composites (75%) produced are GFRP with Thermoset Resins, which inherently lack end-of-life utility due to their unmodifiable structure and design without reuse or recovery in mind.
Consequently, these composites, particularly in Facade Cladding applications, exhibit low circularity potential.

Thermoplastics **Convenience**



"Compared to cured thermoset matrix resins, which are problematic to dispose of and difficult to recycle, thermoplastic matrices are in essence easier to handle during operations since they are repeatedly meltable" (Kiss et al., 2020, p.1)

The need for continuous fibre-reinforced thermoplastics is continually expanding due to their workability facilitating repeatable formation while preserving material integrity.

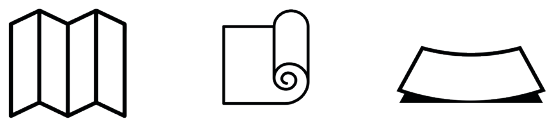
Identified Gap **Strategy**

Sheet — Panel — Sheet — Product — ∞

Chanda & Bhattacharyya (2022) emphasize on the gap of developability for widespread use of Natural Fibre Reinforced Thermoplastics.

In this study, 'developability' will be the principle aim, to prove that biocomposites can transform from flat sheets to cladding panels via composite sheet forming, and potentially back to flat sheets without distortion. This process will not only underscore their reusability and repurposing potential but also ensures the conservation of embodied energy, maximizing value throughout multiple product lifecycles. This offers a tangible approach towards a sustainable, circular industrial strategy across multiple domains.

Planar Sheets of Natural Fibre Reinforced Thermoplastics for Composite Sheet Forming the Desired Cladding Panels.



Emphasizing product over material integrity in circular strategies can preserve product value, and thermoplastics' suitability for processes like composite sheet forming further enhances their circular potential.

DOMAINS

Biological Origins
MATERIAL

Sheet Forming for Cyclic Shaping
MANUFACTURING

Repurpose - Remould
MANAGEMENT

"

If the 'developability' of biocomposites is proven ... **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 valuable lives

(Chanda & Bhattacharyya, 2022, p. 1).

3.7

Circularity Strategies

Material -Product **Integrity**

The strategies by Joustra & Bessai (2021) are grouped by their aim; preserving product or material integrity.

The product integrity focuses on prolonging the lifetime of products and parts. These strategies emphasize on extending product and part lifespans through methods like reuse, maintenance, and refurbishment.

Conversely, material-oriented strategies seek to maintain material quality while finding alternative uses through repurposing and mechanical recycling.

Keeping the product or material as close to its original state as possible, preserving its integrity, is preferred, as this retains the most of the embedded value. `

In this context, biobased thermoplastics reinforced with natural fibres offer a synergic combination of features resulting from the natural constituents & thermoplastic interface.

Such a composite encourages the application of 'structural reuse' i.e. a major circular design strategy that can preserve product & material integrity in composites (Joustra & Bessai, 2021).

Compatible **Methods**

Parallely, reverse thermoforming is a recycling strategy documented by Kiss and coworkers (2020) that deploys reverse-forming of laminates for testing the **direct reuse potential** of continuous fibre-reinforced thermoplastic composite laminates.

For this study, the principles of reverse thermoforming align closely with the 'developability' strategy, making the reuse route proposed by Kiss et al. (2020) an **ideal basis for developing thermoplastic biocomposites**.

Design Aim	**Preserving Product Integrity**		
Circular economy strategies	Long Life	Lifetime Extension	Product Recovery
Actions / Processes	Physical Durability Long use Reuse	Repair Maintenance Adapt Upgrade	Refurbishment Remanufacture Parts harvesting

Design Aim	**Preserving Material Integrity**	
Circular economy strategies	Structural Reuse	Material Recycling
Actions / Processes	Repurpose Resize Reshape	Remould Mechanical Thermal Chemical

Reverse **Thermoforming**

Reverse thermoforming involves reshaping thermoplastic composites into their original form, which presents an opportunity for reuse.

This intricate method relies on matrix thermal stability, enabling multiple reshaping attempts. Though the technique faces challenges such as avoiding creases and fiber misalignment, the process has been mechanized with a specialized setup.

The process involves heating the thermoplastic laminate, with the use of a diaphragm vacuum forming machine, to a specific temperature depending on the material, then reshaping it back to its initial form.

This operation, completed within a short 60-90 second cycle, showcases a promising method for direct reuse of thermoplastic composites. `

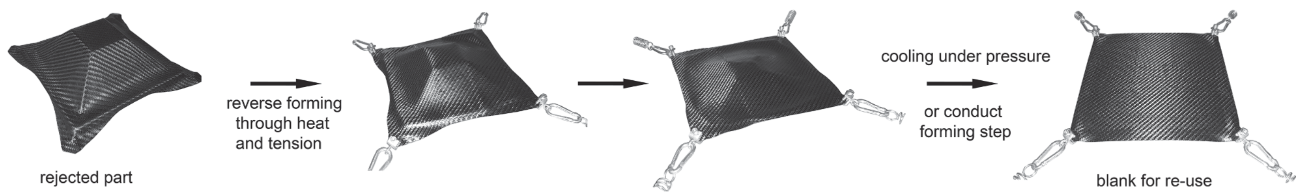


Fig. 3. Reuse route for thermoformed parts by reverse-forming.

3.8

Thermoplastic Matrices

Rising **Interest**

In recent times, there has been rising interest in natural fibre-based composites made from thermoplastic polymers for high-performance applications. Thermoplastics provide higher ease of manufacturing & better design flexibility, as compared to thermosets & elastomers (Andrew & Dhakal, 2022).

Conventional thermoplastics for NFRP are (polyvinyl chloride (PVC), polyethene (PE), polyether–ether ketone (PEEK), polypropylene (PP), acrylonitrile-butadiene-styrene (ABS), nylon) for their remouldability & efficient use of materials (Clyne & Hull, 2019; Todor et al., 2022).

Conventional **Challenge**

In contrast to thermosets, NFRPCs with non-degradable thermoplastics cannot undergo biodegradation but can be easily recycled (Clemons & Caulfield, 2005; Vaisanen et al., 2017).

However, these composites are considered partial biocomposites (See Figure 2) owing to their incompatibility to be broken down through environmental degradation after their intended use (Sain & Panthapulakkal, 2004).

Climate **Conscience**

Petro-based virgin raw materials for producing these thermoplastics are driving environmental awareness among industries and institutions to find alternative matrices in biobased plastics. (Faruk et al., 2012; Vaisanen et al., 2017; Andrew & Dhakal, 2022)

Therefore, the fabrication of green biocomposites employing biopolymers obtained from renewable sources has experienced a renaissance in past decades (Faruk et al., 2012; Andrew & Dhakal, 2022).

Biopolymers
Since the early 1970s, biopolymers, have been attracting the focus of researchers (Ilyas et al., 2021), and the concept of using biobased plastics as matrices is gaining approval, validated by their rapid growth in the market. (Faruk et al., 2012)

The rapid emergence of bioplastics is one of the powerful stories of the last decade. Once billed as biodegradable plastics, the theme for renewably sourced plastics has shifted in recent years to sequestration of CO2 and sustainability.

The focus has shifted to the total “carbon footprint”, and bio-based polymers can replace existing polymers in various sectors and provide new combinations of properties. (Murariu & Dubois, 2016)

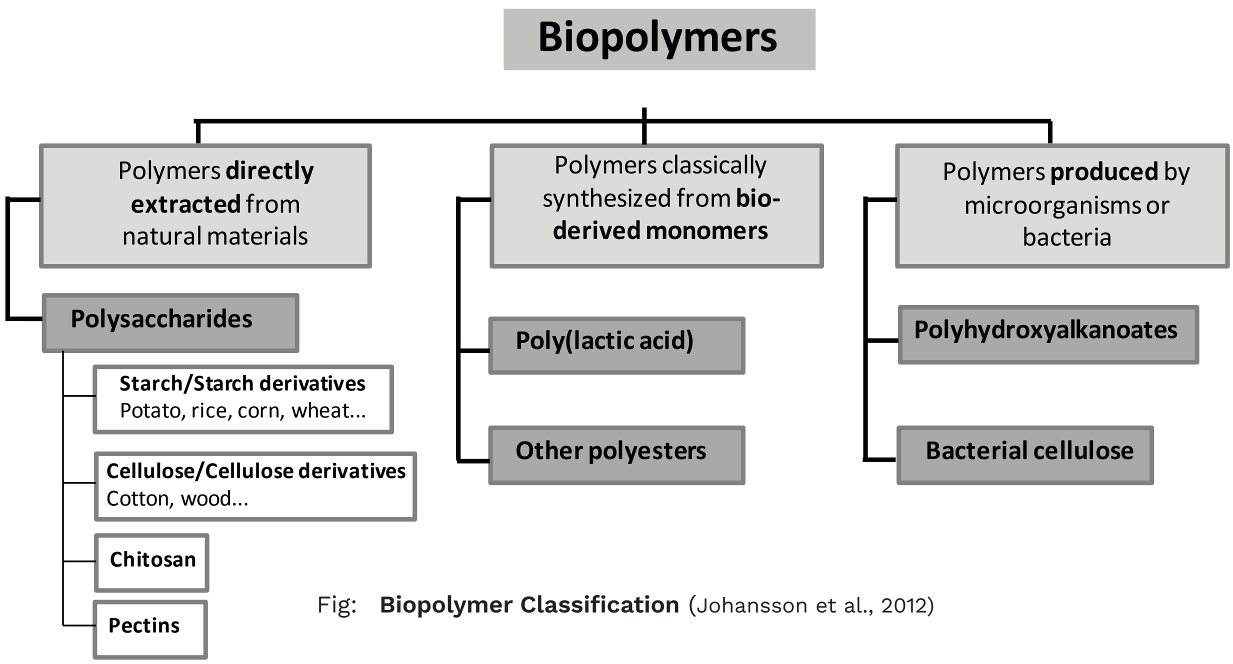


Fig: **Biopolymer Classification** (Johansson et al., 2012)

3.9

Emergent Biopolymers

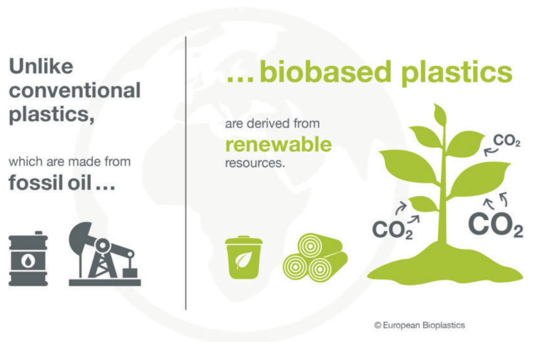
Biopolymer **Definition**

The identical polarities amid the fibres and biopolymers generate biocomposites with superior compatibility & interfacial adhesion, unlike synthetic polymers.

Therefore, even though a generally recognised definition of the concept of “biopolymers” does not exist, we will accept the as follows:

a) biobased and biodegradable;
b) biobased but not biodegradable;
c) based on fossil resources and biodegradable.

(European Bioplastics, 2022; Murariu & Dubois, 2016)



Matrix: Bio-Thermoplastics

Standard bio-based thermoplastic matrices are PLAs, polyglycolic acid (PGA), and poly- βhydroxy alkanoates (PHA). Some are directly developed from naturally occurring sources (starch), while others, like PLA and PHA, are synthesised from fermented sugars (PLA) and vegetable oils (PHA) from biobased feedstocks (Faruk et al., 2012, Vaisanen et al., 2017).

Bioplastics still need to be explored due to their undetermined long-term durability and varying eco impacts due to reliance on petrol-based processing energy. Furthermore, Bioplastics is one of many solutions; however, the complete manufacturing process should be sustainable.

This study is a step towards encouraging the application of biomaterials with narrow and closed loops of resources & energy through determined lifecycles via a circular economy (CE) approach.

> “The potential of bioplastics will shape the future of the plastics industry.”

European Bioplastics ©, 2022

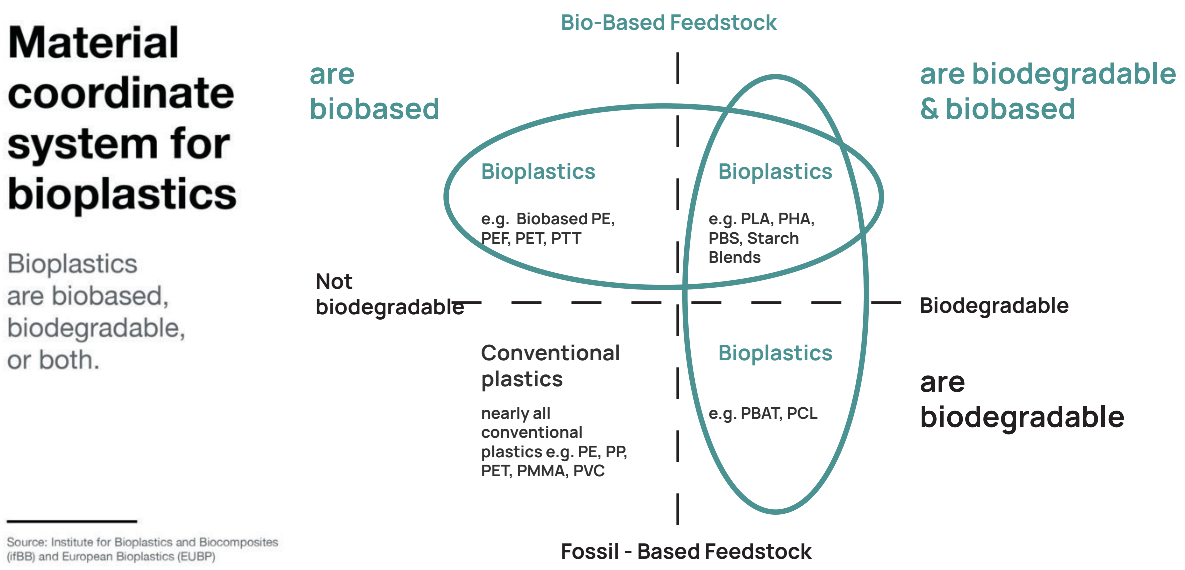


Fig: **Bioplastics Coordinate Graph** (Institute for Bioplastics and Biocomposites (ifBB) European Bioplastics© (EUBP)

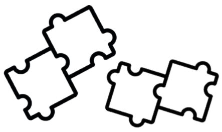
3.10

Composite Design

Design **Process**

The scientific interest of this paper lies in developing biodegradable composites that address the challenges in end-of-life scenarios for composites. The development of the biocomposite will proceed in four stages:

Phase 1
Constituent Material Selection



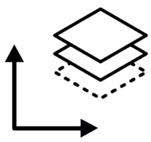
A. The Reinforcement

B. The Matrix

The first step in composite design is to choose the appropriate constituents for the desired end-use application.

The selection factors depend on desired mechanical properties, cost, weight, and environmental conditions.

Phase 2
Configuration & Characterization



Once the materials are selected, the next step is to determine the laminate design, which is the arrangement of layers of composite materials.

The orientation, thickness, and type of fibre and matrix materials in each layer, as these factors can significantly influence the composite's mechanical properties.

The stacking sequence refers to the order of layer arrangement, affecting properties such as strength, stiffness, and thermal expansion.

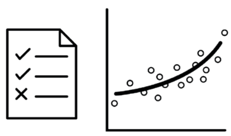
Phase 3
Manufacturing Process Selection

The manufacturing process for composite materials can significantly impact the final properties of the composite, production costs and time.

Standard composite manufacturing processes include hand lay-up, vacuum bagging, and resin transfer moulding (RTM).

The choice of the manufacturing process depends on component shape and size, material properties, production volume, & cost constraints.

Phase 4
Structural Criteria & Case Study



After selecting materials, designing the laminate, and choosing a manufacturing process, the composite design should undergo structural analysis to ensure it meets the performance requirements for the intended application.

Experimental testing, such as tensile and flexural tests, will record properties and ensure that the composite performs as intended. The results will input data into numerical simulations, such as finite element analysis (FEA), to predict the composite's behaviour under various loads and conditions.

The four-part process is iterative, meaning that each step may require adjustments to previous steps based on the results of the subsequent steps. This process continues until the composite design meets all performance requirements and constraints for the intended application.

3.11

Phase 1A Reinforcement Selection

Reinforcing **Natural Fibre**

As discussed, Fibres are the primary components that occupy the most significant volume in the biocomposite and withstand the external design load. Therefore, this thesis reviewed comprehensive literature and previous work at TU Delft to conclusively propose a suitable natural fibre for the end-application of exterior facade cladding.

Upon analysis, Flax Fibres (scientific name- Linum usitatissimum) were the best fit due to various factors:

1. Their exceptional tensile strength from bast origins (Mohanty et al., 2005)
2. Wide availability in Europe (Yan et al., 2013; Baley et al., 2019).
3. The presence of an industrial sector: active selection of varieties, experienced manufacturers and companies specialised in extracting plant fibres
4. The mean fibre diameter (df = 16.8±2.7 μm, fibre diameter — 12 to 30 μm) is similar to E glass fibres used for polymer reinforcement.
5. Lightweight fibre with good mechanical properties (Yan et al., 2013; Baley et al., 2019)

Fibre	Density	Young's Modulus (GPa)	Tensile Strength (MPa)	Elongation (%)
Sugar palm	1.5	10.4	421.4	9.8
Bamboo	0.6–1.1	11–17	140–230	-
Cotton	1.5–1.6	5.5–12.6	287–597	7–8
Flax	1.54	27–85	345–2000	1–4
Hemp	1.47	17–70	368–800	1.6
Jute	1.44	10–30	393–773	1.5–1.8
Kenaf	1.2	14–53	240–930	1.6
Ramie	1.5–1.56	27–128	400–1000	1–4

Fig: **Mechanical Properties of Different Plant Fibres** (Oksman et al., 2003; Aisyah et al., 2021; Faruk et al., 2012)

Why **Flax?**

Flax, or the common Flax or linseed, is a flowering plant, Linum usitatissimum, in the family Linaceae. It is a widely used bio-fibre cultivated as a cash crop in temperate climatic regions (France, Belgium). In a comprehensive review of various aspects by Libo Yan and co-workers (Yan et al., 2014), it was observed that Flax had specific mechanical properties suitable for building construction work.

As a result, Flax is produced in reasonably good quantities worldwide (868 Kilo Tons in 2018) compared to other natural fibres like Kenaf, Sisal, and Hemp, which have much lower global production.

Properties of **Flax**

In previous research at TU Delft (Merhi, 2022), Flax fibre ranked high to be a considerably performative fibre for facade cladding applications among all five other types of fibres (Hemp, Jute, Sisal, Softwood) w.r.t Stiffness – 50-70 GPa and Ultimate Stress – 500-900 MPa.

The table below summarises the central values of the mechanical properties of natural fibre-reinforced composites published by companies or in recent studies comprehensively reviewed by Morales and co-workers (2017).

Composite	Tensile Strength (MPa)	Young Modulus (GPa)	Flexural Strength (MPa)
Flax UD */Polyester	198	20	229
Flax Biaxial/Polyester	85	8.7	135
Flax UD/Epoxy	222	30	271
Flax Mat/Polyethylene	81	8	130
Flax/Polypropylene	50	5.4	107
Flax UD/Epoxy	383	32	330
Flax Plain/Epoxy	115	16.2	130
Flax UD/Epoxy	270	28	226
Flax UD/Epoxy	365	35	300
Flax/Polyester	277	23.4	239.2

Fig :
Mechanical Properties of Flax Reinforced Composites

(Adapted by Morales et al., 2017)

3.12

Flax Fibre Reinforcement

Flax **Fibre Journey**

Below is a visual journey of flax fibres from the harvesting stage to extraction and being processed for yarn in technical textile applications. (Source: The Libeco Blog, 2018)

Flax **Structure**

In their investigation of Flax fibres, Libo Yan et al. 2013 found that flax fibres primarily comprise cellulose, hemicellulose, wax, lignin, and pectin in varying quantities. These fibres, which are produced in the stems of the flax bast plant, are commonly used to make linen textiles by spinning the fine and regular long fibres into yarns.

Flax plant ranges in length up to 90 cm, and the cross-section of a bundle contains between 10-40 strong fibres along its stem with an average diameter of 12–16 μm. The high cellulose content (approximately 70%) makes flax suitable for use as reinforcement in composites due to increased fibre wettability and adhesion characteristics. Flax fibres have multiple formats or configurations as reinforcement material. Monofilament fibres are processed into mats (non-woven pressed fibres), rovings (bundles of fibres), yarns (rovings spun into threads) and fabrics (yarns weaved into textiles).

Flax **Characteristics**

The main concern in using Flax fibre in building construction is that it is hydrophilic, leading to high moisture uptake, which lowers the tensile properties of the fibres themselves (Yan et al., 2014) and consequently lowers the mechanical properties of bio-composite. While research findings are available about the impact of tensile properties due to the treatment of fibres by additives, improvement in moisture resistance has yet to be recorded.

The durability of bio-composite is a critical concern that needs further research. Stamboulis et al. (2000) presented an improvement in moisture absorption and swelling properties by 30% by using a Duralin-treated Flax composite compared to untreated flax composites.

The durability of flax-reinforced composites can be improved by understanding the interfacial properties with matrices, and therein lies a research gap as per the literature reviewed. (Yan et al., 2014)

Libo Yan & the authors (2011) noted that the architecture of the fibre reinforcement directly influences the manufacturing technique used to produce a composite, as the fibre length or aspect ratio significantly impacts the processing techniques. On the other hand, the manufacturing method greatly influences fibre length distribution, affecting the tensile properties.

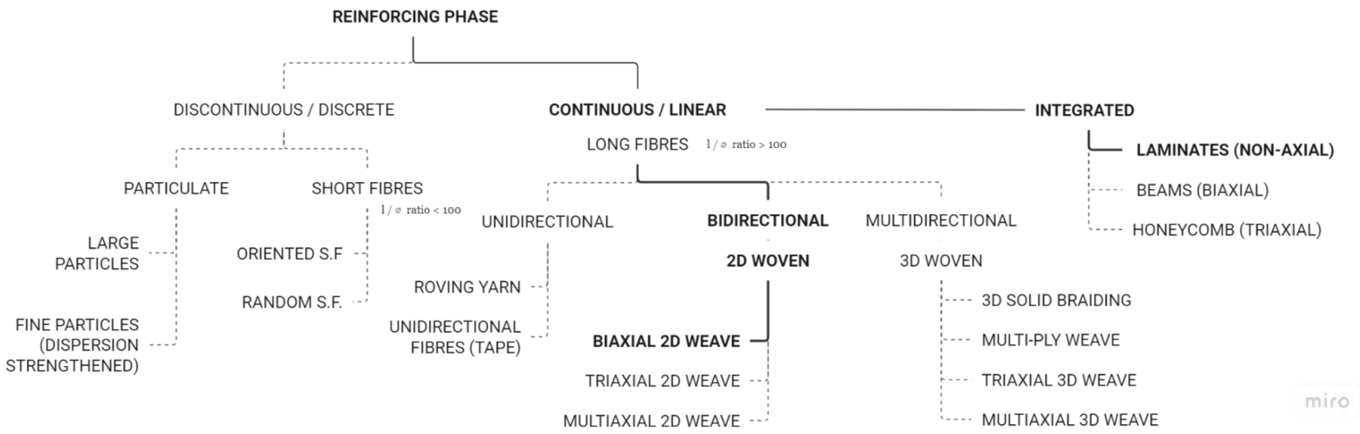
3.13

Proposed Architecture

Classification of **Flax**

In the present literature, there was a gap in the classification of Natural Flax. Below is a summarised material map focusing on the arrangement, length and spatiality to classify between discontinuous fibre and continuous flax reinforcements.

The following classification orders composites according to their reinforcement phase within the realm of Natural Flax. These can range from non-axial to multiaxial systems, where yarns are introduced from four or more directions.



REDO Classification of Flax reinforcement structures based on Axis and Dimension

Continous **Architecture**

The structure of continuous fibre composites can be either single-layer or multilayered.

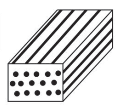
Typical short or discontinuous Flax is a single-layer (homogenous) composite.

In contrast, unidirectionally continuous or biaxially woven architectures are multilayer composites, where the layer/ply of flax fibres are laid upon each other within the adhesion of a matrix system (Staab, 2015).

Continuous fibres/woven architectures provide superior mechanical strength and properties compared to discontinuous or particulate fibre systems. This study will therefore focus on composites composed of continuous fibre systems.

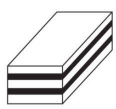
Schematics of both structures in fibrous composites are in the Figure below.

Single-Layer Flax Composites:



Composites are either unidirectional flax fibres or quasi-isotropic reinforcement. The material response of a continuous fibre composite is generally isotropic.

Multilayered Flax Composites:



Structural composites are either laminate (layered plies) or sandwich panels. The material response of a continuous fibre composite depends on the configuration of the layers.

3.14

Sourcing Reinforcement

Flax **Mediums**

The ideal weave architecture is dependent on the specific needs of the facade cladding application. The end-use application requires the composite to have good mechanical properties, durability and a potential aesthetic appeal.

Market **Analysis**

Technical Flax is available in multiple formats for reinforcement in composites. Based on the market research conducted for this study, as well as prior research at TU Delft, EasyComposites, EU (2023) – a prominent materials supplier for composites in the UK and Europe – offers the following flax formats:

1) Non Woven Flax Fibre Mat
Non-woven flax fibre mats are a unique composite reinforcement created using non-woven or knitted flax fibres. Instead, the fibres are either randomly placed or specifically oriented and bonded with a resin or another binding agent.
These mats are generally lightweight, flexible, and have consistent properties in multiple directions. They are used for insulation, filtration, and lightweight composite materials.

2) Unidirectional Flax Fiber Tape
A unidirectional flax fibre tape is a composite reinforcement where flax fibres are aligned in one direction and bonded with a lightweight backing, such as a thin resin layer or a textile material.
This design provides a high strength-to-weight ratio along the fibres, making it perfect for applications that need enhanced strength and rigidity in a particular direction.

Manufacturer : Eco-technilin France

Authorised EU Distributor : Easy Composites

3) Cross-Stitched Unidirectional Flax Fibre
The cross-stitched unidirectional flax fibre is a reinforcement material with unidirectionally arranged flax fibres secured with cross-stitched lightweight flax thread. This stitch offers increased stability and better delamination or fibre separation resistance than standard unidirectional materials.
Additionally, the cross-stitching allows it to maintain the handling properties of woven fabric while preserving the unidirectional orientation of the material.

4) Twill Flax Fiber Cloth
The twill flax fibre cloth is a woven composite reinforcement made from flax fibres and exhibits a unique diagonal pattern. In the twill weave, fibres are interlaced to produce longer floats and fewer interlacing points than in a plain weave.
This results in greater drapability enhanced mechanical properties, and an attractive visual appearance. Twill flax fibre cloth is versatile and can be used in applications such as structural components, automotive parts, and facade cladding.




3.15

Selected Reinforcement

Selected Weave: **Twill**

Between plain weave and twill weave for flax composite, Twill weave offers certain advantages that make it a better choice for reinforcing materials for an active structural application.

Justification/**Rationale**

1) Drapability

Twill weave has better drapability than plain weave, as it is more flexible and readily conforms to complex shapes. The diagonal pattern in the twill weave creates longer floats, making it more pliable than the plain weave's simple over-under pattern.

2) Mechanical Properties

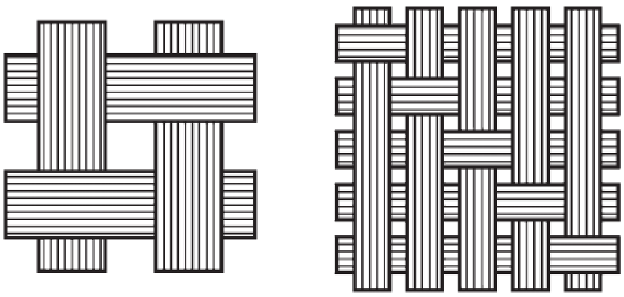
Twill weave can provide improved mechanical properties, such as higher tensile strength and better impact resistance, compared to plain weaves.
The longer floats and fewer interlacing points in the twill weave allow for a higher fibre volume fraction, which can lead to enhanced mechanical properties.

3) Aesthetic appeal

Twill weave has a distinctive diagonal pattern, giving it a more appealing visual appearance than the simple crisscross pattern of the plain weave.
Important in applications where aesthetics play a role in selecting the weave.

4) Reduced yarn crimp

Yarns in twill weave have less crimp (bends and waves) than those in plain weave, as they have few interlacing points.
Reduced crimp can result in better load transfer between fibres and improved mechanical properties.



Source Image: Retrieved from Easy Composites

3.16

Phase 1B Matrix Selection

Polymeric **Mediums**

As discussed in section- Polymer Matrix Systems, the matrix phase provides structural shape-rigidity and transfers the load to the reinforcing fibres by adhesion/ friction. In addition, it protects the fibres from chemicals and corrosion, influencing overall impact and ductility, which is essential for facade elements.

Concerns with **Partial Biobased**

Merhi's 2022 study at TU Delft highlighted the utilisation of bio-based epoxy resin, which contained 38% bio-based content, as an environmentally friendly substitute. Notably, composites made with non-biodegradable polymers exhibit superior mechanical attributes when the resin content is around 50%.

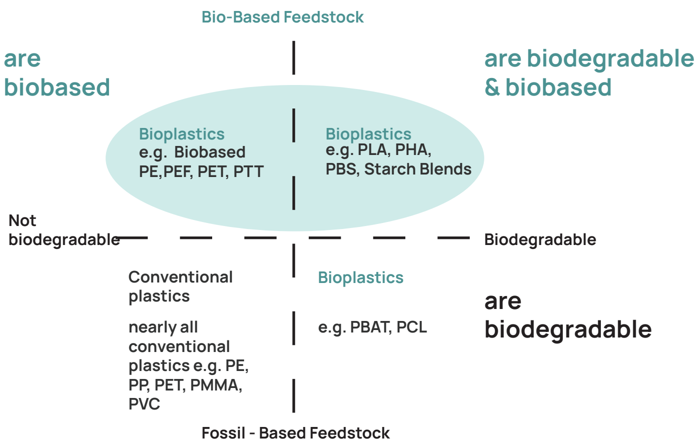
However, these materials are not eco-friendly alternatives due to the non-biodegradable nature of the reinforcing polymers. Furthermore, although these resins can satisfy recyclability requirements, undetermined end-of-life scenarios factor into the decision to use such resins (Morales et al., 2017).

Research **Intent**

As Morales and co-authors (2017) state, "The main scientific interest has been in the development of a biodegradable composite material that can decrease carbon footprints and petroleum dependence." (p.4).

However, the challenge remains, as the available biodegradable products are expensive and have inferior properties.

This study considered three domains to address the challenge - material origins, manufacturing and management - while choosing the appropriate biopolymer for the matrix phase.



Search: Biobased & Biodegradable
The probe region was for biobased polymers.
Pre-requisites of this paper's intended circular strategy further narrowed the scope to biobased thermoplastics.

Biodegradability was the additional starting point to allow the material's biological origin to come full circle.

Thus the final search attributes were:

- 100% biomass/ feedstock-based origins
- full biodegradability;
- minimal processing & operational measures;
- easy handling/storage conditions;
- commercial availability in Europe.

Polylactic acid (PLA) emerged as the most suitable fit for these benchmarks.

Why **PLA ?**

Polylactic acid or polylactide (PLA) is a bio-sourced and biodegradable (under industrial composting conditions) thermoplastic aliphatic bio poly (ester). It is the most widely utilized and promising alternative for conventional petroleum-based polymers due to its renewability, recyclability, biodegradability and compostability (Mohanty et al, 2000; Nurul et al., 2016; Siakeng eT al., 2018; Ilyas et al., 2021; Kazmi et al. 2023)

- Sequesters carbon
- Conserves substantial energy during production.
- Recyclable and compostable (industrial)
- Mehanical characteristics can be engineered.

PLA was first synthesized by Theophile-Jules Pelouze in 1845 but was not fully utilized until 1954 by DuPont. DuPont introduced PET technology to PLA, and NatureWorksTM (Cargill Dow Polymers) invested 300 million USD to mass produce PLA in 2002, and since then, after evolving production, PLA has been recently available globally (Nurul et al., 2016; Paciorek-Sadowska et al., 2019).

Bioplastics Coordinate Graph
(Institute for Bioplastics and Biocomposites (ifBB) European Bioplastics© (EUBP)

3.17

PLA Matrix

PLA **Production**

It is industrially obtained from the fermentation of polysaccharides or sugars extracted from agricultural crops such as corn (maize), potato, cassava (cane molasses), sugar-beet pulp.

PLA is significant in global biodegradable polymer production, accounting for 10.3% of the total, equivalent to 0.2 million tonnes (Siakeng et al., 2018; Paciorek-Sadowska et al., 2019).

New technological progress is expected to derive PLA from a wide range of fermentable sugar sources (non-food cellulosic biomass, agro waste, non-food crops), allowing carbon-neutral cycles by diversifying PLA feedstocks other than corn-derived dextrose (Murariu & Dubois, 2016).

PLA **Synthesis**

The starch chains of maise & cassava convert into sugar. These sugars are fermented and dehydrated to obtain chains of lactide or lactic acid monomers, ultimately polymerised into PLA. (Mohanty et al., 2000). Two-step ring-opening polymerisation of Lactic Acid (LA) is the most common method to synthesise PLA (Garlotta, 2001). The mechanical properties of neat PLA are relatively elevated, with a modulus of 3 GPa and high tensile strength of 50–70 MPa. (Nurul et al., 2016)

PLA **Relevance**

Ray and Okamoto (2003) explored the versatility of PLA, who manufactured nano-composites using PLA, demonstrating its potential as a polymer in bio-composite production.

As a result, PLA-based products have made significant inroads into diverse fields such as packaging, textiles, biomedical applications, structural components, and automotive interiors, offering an eco-friendly alternative to petroleum-based polymers (Ilyas et al., 2021; Shao et al., 2022).

The widespread adoption of PLA in various industrial sectors is driven by its low thermal conductivity, minimal weight and exceptional manufacturing versatility.

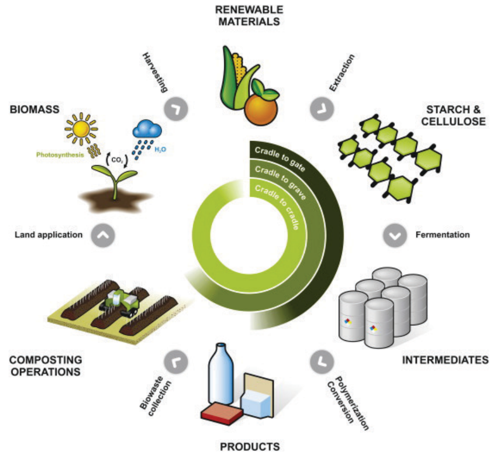


Figure: The Biological life cycle of PLA from corn and sugar-beet to compost (Castro-Aguirre et al., 2016)

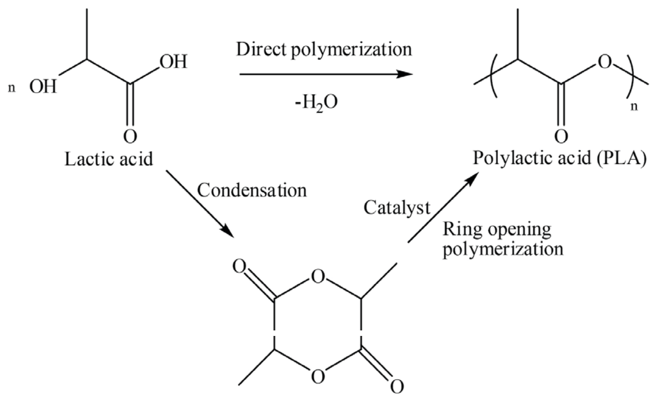


Fig: **Synthesis of poly (lactic) acid (PLA)**
Adapted from (Nurul et al., 2016)

PLA **Processing**

Processing can use various techniques, including injection moulding, film extrusion, blow moulding, thermoforming, fibre spinning, and film-forming. (Ilyas et al., 2021) The life cycle assessment of PLA underscores its potential market success, highlighting its biodegradability, renewability, and lower carbon dioxide emissions.
In addition, compared to conventional composites, the PLA supply chain requires less transportation, reducing greenhouse gas emissions (Siakeng et al., 2018). Advancements in production technologies have now made PLA more accessible and affordable.

However, due to previous constraints on the bulk availability of commercial PLA, commercial fibrous composites with PLA as a matrix are relatively limited in the current market. (Nurul et al., 2016; Kazmi et al., 2023).

3.18

PLA-Flax Composites

Mechanical **Properties**

The mechanical properties of polylactic acid (PLA) and flax fibre composites have been a subject of increasing interest in the scientific community for two decades (Kazmi et al., 2023).

Therefore, to achieve a suitable composite design, it is imperative to understand the properties of Flax-PLA composites recorded in various seminal studies.

Adaptable Combination

The thermoplastic nature of PLA and improvements in interfacial bonding and temperature characteristics make flax/PLA composites ideal for use in automotive structural applications, as Nassiopoulos and Njuguna (2015) concluded.

Manral et al. (2020) provided experimental evidence that flax-PLA composites outperformed other natural fibre PLA composites in dynamic mechanical properties such as glass transition temperature, loss modulus and storage modulus.

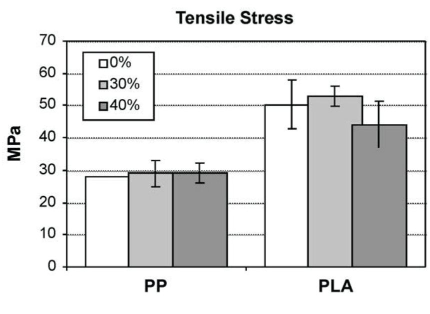
Mechanical Strength

In a comparative study, Oksman et al. (2003) demonstrated that the mechanical strength of PLA and flax fibre composites was approximately 50% higher than that of polypropylene/flax composites.

Similarly, Bax & Müssig (2008) reported good tensile and impact properties to suggest that PLA composites could potentially replace petrochemical polymers, contributing to an enhanced ecological balance in the supply chain.

Graphs of PLA vs. PP Flax Composites in Tensile Testing

Oksman et al. (2003)



Composite	Tensile Strength (MPa)	Young Modulus (GPa)	Flexural Strength (MPa)
Flax 2×2/PLA	110	14	123
Flax Plain/PLA	99.5	13.7	125.8
Flax/PLA	44–107.0	6.3–8.0	-
Kenaf/PLA	60–223	6.4–23.5	254
Jute/PLA	55.3–100.5	1.7–8.5	75.9–84.5

(*Adapted by Morales et al., 2017)

Thermal Behaviour

Couture et al. (2016) suggested the possibility of using flax-PLA composites in engineering applications if their thermal stability and long-term behaviour are wel understood, despite PLA's current limitations in structural applications.

Higher Fibre Ratio

Bayerl et al. (2014) highlighted the significant influence of fibre presence and structure on the degradation behaviour of PLA composites, a key consideration when designing parts intended for biodegradability.
Kazmi et al. (2023) also validated the reported higher biodegradation rates at higher fibre contents.

Higher PLA Ratio

A relationship between the mechanical properties and hydrophilicity of flax-PLA composites was discovered by Bulota and Budtova (2015). They reported that an increase in the PLA ratio enhanced the mechanical properties and hydrophobicity.

Challenges

Notably, several structural shortcomings have been observed in Flax PLA composites.
These include moisture sensitivity, inadequate fire resistance, a limited operating temperature range due to PLA's low glass transition temperature (Tg= 65 C), a capped maximum processing temperature due to the natural flax fibres' highest degradation temperature (~200 C), impact resistance, and durability when exposed to natural elements and UV light degradation. These are significant areas of ongoing research for this material combination.

Future Prospects

Notably, new studies are unveiling some favourable characteristics of PLA composites. For example, recent studies point to PLA's higher glass-transition temperature, flame retardant properties, and impact resistance. Additionally, successful outcomes have been reported from treating fibres using Ti02 and Duracilin (Libo Yan et al., 2014; Morales et al., 2017).

In conclusion, the discussed findings suggest that PLA is an effective matrix material for natural fibre composites, with a significant improvement in composite strength observed when using flax fibres as reinforcement.

The research highlights the potential for PLA and flax fibre composites in various industrial applications.

3.19

PLA Mediums

Market **Research**

Underpinned by extensive market research, the present study investigated the availability and procurement of Polylactic Acid (PLA) mediums for European composite production.

Commercial PLA has been diversified into several formats to cater to different applications, production methodologies, and the varying demands of assorted industries.

The typical formats available during the investigation were:

PLA **Pellets**

These are small, cylindrical pieces of PLA that are used in injection moulding and extrusion processes. Available in varied sizes and colours, they provide product design and application flexibility.

PLA **Film**

These thin sheets of PLA are used in eco-packaging and labelling applications. Depending on the desired application, the film's thickness can vary from 15 um to 100 um & more, allowing for different rigidity, transparency, and permeability.

PLA **Polyol Resin**

This form of PLA is chemically modified for use as a bio-photopolymer resin for SLS 3D printing. It is typically available in liquid form and is designed to have optimal properties for UV laser printing, such as appropriate viscosity and cure rates.

PLA **Filament**

This thin, continuous PLA strand is specifically designed for 3D printing. It comes in various diameters, typically 1.75mm or 2.85mm, and it can be produced with different additives to modify its properties, such as colour or aesthetic effects.

PLA **Foam**

This lightweight, porous form of PLA is used for insulation, cushioning, or packaging. It can be produced in various densities and sizes to suit specific applications.

Selected **Mediums**

The chosen fibre architecture critically influences the choice of PLA medium. In the context of this research, the PLA medium needs to enable uniform consolidation with the woven reinforcement.

The selected PLA format not only dictates the manufacturing method but also significantly impacts the ultimate quality of the composite. Therefore, formats like Foam, Filament, and Pellets were deemed unsuitable due to their structural constraints.

Given the nature of the reinforcement structure for this study, **PLA Film and PLA Polyol Resin** emerged as the most compatible mediums to fabricate a sheet of natural fibre-reinforced polymeric composite (NFPC).

Pellets

Film

Polyol Resin

Filament

Foam

3.20

Procurement of PLA

Based on an extensive literature review (Salman et al., 2015; Morales, 2017; Merhi, 2022; Kazmi et al., 2023), these mediums (film and polyol resin) were viable for effective material consolidation and performance outcomes in the final composite structure.

PLA Film

Upon reviewing state-of-the-art, thermoplastic films have been scientifically proven to be a viable medium to manufacture sheet-consolidated composites potentially. (Salman et al., 2015; Morales et al., 2017; Kazmi et al., 2023).
Furthermore, according to Morales et al. (2017), PLA film, with its biodegradability and compatibility with the Resin Film Infusion (RFI) manufacturing process, can achieve high mechanical properties once the process parameters are optimised.

Sourcing
For this research, PLA film samples were sourced from **Bleher Folientechnik GmbH,** a company recognised for producing industrially compostable plastic films from renewable resources.

Production
The production of PLA film involves extruding molten PLA through a flat-die system, followed by rapid cooling. The thickness of the film can be manipulated during this process to cater to specific applications.

Attributes
The company's Optimont® PLA films are noted for their impressive characteristics, including a high moisture transfer rate, an inherent surface tension of 36-38 mN/m, commendable UV light transparency, and scratch resistance.
These films are also food-safe, reflecting their potential for diverse applications. In addition, the films are available in thicknesses including 20, 25, 30, 40, 50, 75, and 100 μm.

Certified by DIN CERTCO according to DIN EN 13432 and ISCC Plus, these PLA films meet strict compostability standards, substantiating their environmental credentials.

Material Handling
Optimont® PLA films necessitate specific conditions. Their storage must be shielded from extremes of humidity and heat. The recommendation is to store the films below 40°C in dry locations, ideally in their original packaging.

PLA Polyol Resin

The use of PLA Polyol resin presents theoretical potential as a PLA-based alternative to certain epoxy resins currently employed in the composite industry.

Sourcing
The PLA Polyol resin explored in this study was sourced from a materials supplier based in the Netherlands. The specific product of interest is **eSUN's eResin-PLA Polyol**, launched in 2020.

Production
PLA Polyol is a modified form of polylactic acid, particularly suited for use in selective laser sintering (SLS), a type of ultraviolet-based 3D printing. Its molecular structure is characterised by multiple hydroxyl (-OH) groups.

This feature imparts a high degree of **fluidity** to the resin, making it advantageous for specific applications. Its production process involves the synthesis, modification, and formulation development of photosensitive resin conducted in eSUN's Xiaogan factory, which maintains a stable polylactic acid polyol production capacity.

Attributes
Bio-based resins, such as eResin-PLA, are noted for their low odour and reduced irritation, the resilience that allows drilling without the risk of cracking, and enhances user comfort and suitability for diverse applications, including educational contexts.

This resin exhibits outstanding toughness and low odour and results in printed parts with smooth surfaces. In addition, with a certification per EN71-3 toy standards, it guarantees safety in use.

Material Handling
The resin should be stored in a cool, dark place and sealed with an opaque container. The resin can be cured in 395 nm UV light, which is safe for handling and vision.

3.21

Phase 2 Configuration & Structure

Following the material selection, a composite is largely influenced by its structural design and organisation. Composites with continuous phase fibre reinforcements can be either single-layered (Prepreg sheets) or multilayered in structure.

Behaviour **Determinants**

Multilayered composites are low-density structural composites having distinct material behaviour and can be further classified as laminar composites or sandwich panels.

Unlike conventional engineering materials, continuous fibrous composites are generally heterogeneous and do not behave as isotropic materials, meaning composite properties behave differently based on directionality and orientation.

Most composites behave as either anisotropic or orthotropic materials depending on their structure of production & reinforcement orientation. (Staab, 2015)

Flax in **Laminar Composites**

Flax-based composites are primarily seen as reinforcement in laminar composites in facade applications, as noted by previous work at TU Delft (Merhi, 2022) and extensive literature reviewed (S.M.R. Kazmi et al., 2023). This study will therefore forward on laminar composites composed of layers of biaxially woven flax fabrics.

Laminates

A lamina is a thin layer called a ply, usually containing unidirectional or woven fabrics in a fabric pattern. Unidirectional Plies have fibres in a longitudinal direction (1), while Fabric plies have fibres in both longitudinal (1) and transverse (2) directions.

A **laminate -**
is created by stacking multiple layers of material in predetermined orientations to achieve a desired structure.

A **laminar composite -**
therefore, refers to interconnected two-dimensional sheets or panels (plies or laminae).

Potential **Configuration**

In the past six decades, laminar composites have found structural applications in industries such as aircraft, automotive, marine, and building/civil infrastructure due to their weight advantage and better stiffness and strength properties, as compared to traditional structural materials (Gürdale et al., 1999).

In addition, they exhibit high tensile, flexural, and torsional strengths & stiffnesses and thus have immense potential to be used in applications which require structural integrity.

For Reference:

Isotropic Materials -
Properties remain the same when tested in different directions. (often randomly oriented discontinuous reinforcements exhibit isotropic material responses)

Anisotropic Materials -
Properties are directionally dependent, and exhibit properties that are different based on all directionality, location, or where force is applied to the material.

Orthotropic Materials -
Mechanical properties are unique in three mutually perpendicular directions.

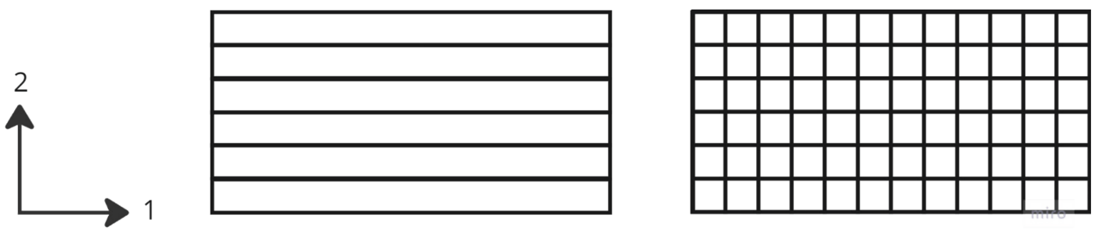


Fig: Own Image, (L-R) Axis, Laminate and Laminar Composites

3.22

Laminar Classification

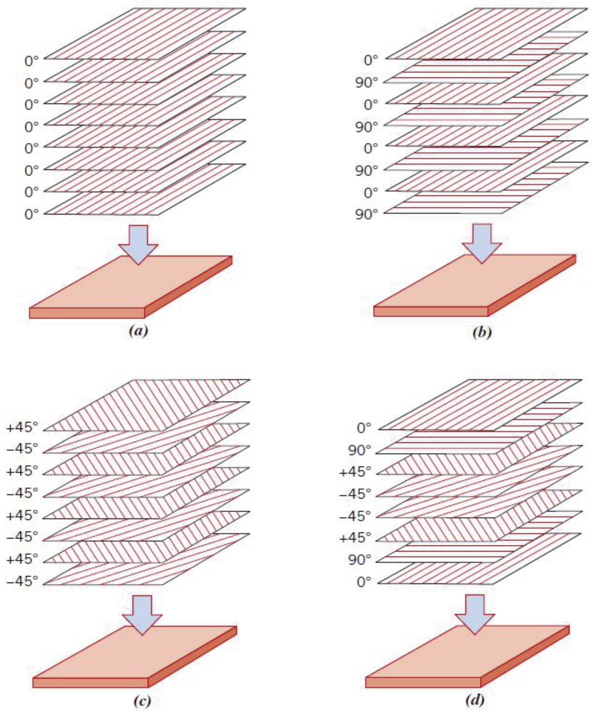
In the building industry, laminates are used in components such as bridge parts, long-span roof structures, beams, structural panels, and roof panels, as these materials undergo more minor deformations and carry larger static loads than their counterparts (Gürdale et al., 1999).

However, laminar composites' properties depend on the structural elements' geometrical design alongside the constituent's properties. (Staab, 2015)

Categorising **Laminar**

These material layers possess high strength in a preferred direction, as commonly observed in aligned fibrous composites. Properties depend on the variation of the high-strength direction (warp or weft) from one layer to another.

In this regard, there are four classes of laminar composites:



a) Unidirectional: The orientation of high-strength direction for all laminae is the same;

b) Cross-ply: Laminates with alternating high-strength layer orientations of 0° & 90°;

c) Angle-ply: Layers alternate between + & - high-strength angled orientations e.g., ±45°

d) Multidirectional: Laminates have several high-strength orientations 0°, ±45°, 90.

Polymeric Laminar

Polymeric Laminates can be constructed using woven fibres embedded in a plastic matrix. These materials exhibit a relatively high level of isotropy within the plane.

However, the overall strength and uniformity of properties (scientifically called isotropy) of the stacked laminate depends on factors such as

1. Fibre Typology
2. The number of Layers
3. The Sequence of Orientation

Configuration for **Lay-up**

The material lay-up & the fibre volume fraction can have a considerable effect on the mechanical strength, thickness consistency & consolidation of the composites, owing to the general rule of mixtures.

The lay-up was chosen according to literature & experimental studies.

Morales et al. (2017) and Kazmi et al.(2023) recommend that the fibre thickness between two polymer layers should be minimum for the targeted mass fraction. This translates into symmetry for maximum permeability between layers.

Intent : Efficient Consolidation

Kazmi, Jayaraman and Das (2023) recorded excellent consolidation with a 0/0/0/0 layout while minimising the manufacturing time.

The **symmetrical layout ensured the lowest time** required for the **PLA to impregnate the fibres**, as the polymer had to flow less than a millimetre through the fibres.

The biaxial weave architecture selected for this study is the fine twill weave reinforcement (with the grammage 300g/m2) sourced from (Easy Composites supplier) **Ecotechnilin,** a leading producer and distributor in the EU for technical flax.

Kazmi & co-authors noted that the fibre architecture of the twill weave is directionless (there is no preferred higher strength direction in tensile strength comparisons), as validated by the datasheet of the woven flax proposed, which notes similar yield strength in both Warp and Weft directions (L-FLAXDRY-BL300-30, Ecotechnilin).

3.23

Stack Configuration

Property	Data		Unit	Standard
	Weft direction	Warp direction		
Tensile Strength	75 ±4	78 ±2	MPa	ISO 527-5
Young Modulus[2]	5 ±1	6 ±1	GPa	ISO 527-5
Elongation at break	2,4 ±0,2	3,2 ±0,2	%	ISO 527-5
Thickness of 1 impregnated ply	0,83 ±0,02		mm	NF EN ISO 5084

Fig: Ecotechnilin Technical Data Sheet - Attached in Appendix

Configuration: **Unidirectional**

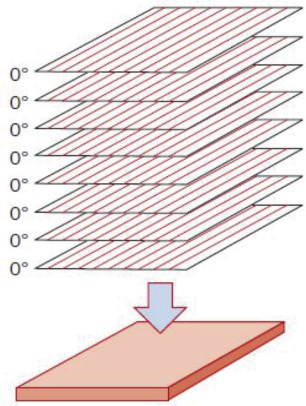
In the interests of **maximum consolidation** & uniformity, all reinforcement layers will be aligned in the same direction for the layup during manufacturing for the middle layers.

The resultant composite can be categorised as a unidirectional laminate with cross-ply surfaces. This is achievable due to the similar range of tensile strength values in both warp and weft directions.

Review: **Permeability**

Antonucci et al. (2003) established that the permeability of reinforcement is the most critical parameter in controlling fibre wetting. Therefore, fibre wetting, or the impregnation of the matrix, majorly influences the quality of the composite part.

According to the findings of Liotier & coworkers (2015) and Kazmi & coworkers (2023), a symmetrical layout with a fine twill would allow PLA the highest In-plane Permeability 460 x 10-12/m2 during manufacturing, as the PLA will melt and flow through the fibres at a uniform flow rate.



Orientation of high-strength direction for all laminae is the same - **Unidirectional Lay Up (a)**

This study forwards the layering of fine twill reinforcements in a unidirectional configuration. The **stack sequencing** marks the end of configuration & material characterisation for the composite.

After the initial stacking of layers, various production techniques can be used to fabricate the material, such as autoclave moulding, pressure-bag moulding, and vacuum bag moulding.

3.24

Phase 3 Production & Processing

Production **Fundamentals**

“The production of biocomposites prerequisites a deep understanding and knowledge of the constituent materials to achieve the specific properties” (Andrew & Dhakal, 2021, p.2).

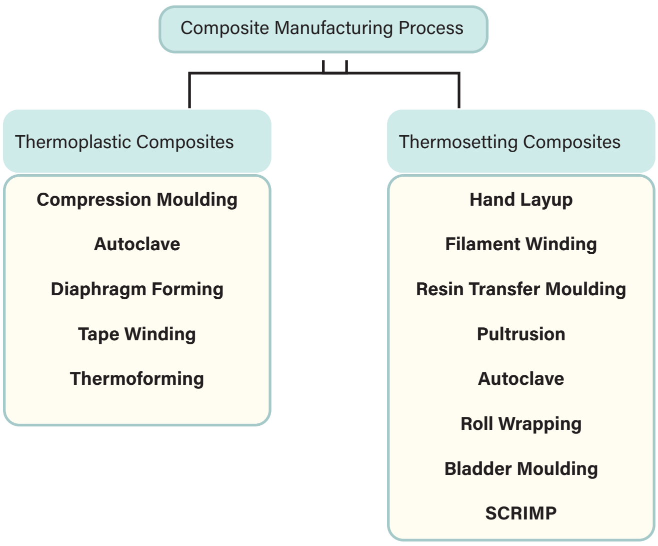
Interestingly, the production of laminar composites has often leveraged numerous forming and bonding techniques post the materials’ stacking sequence & configuration across innovative research (Salman et al., 2015; Morales, 2017; Kazmi et al., 2023).

The choice to implement one or more production techniques (which often include hand lay-up, vacuum bagging, resin transfer infusion, and compression moulding) is shaped by the material selection, preferred medium, and the desired mechanical performance of the composite (Andrew & Dhakal, 2021).

Method **Classification**

This next section will explore the pivotal aspects of biocomposites fabrication.

According to the latest review by Aravindh et al. (2022), the most recent and widely used production methods for continuous fibre composites are as below:



3.25

Selective Methods

Composite **Objectives**

As the design builds on the conclusions of Phase 1 and Phase 2, this study aims to manufacture laminar composites in sheet form.

Production will be achieved through the use of twill-woven fabric in combination with promising mediums such as PLA Resin and PLA Film.

Review **Findings**

A series of experimental studies were referred to understand the status of circular methods for processing laminar biocomposites, including work by Kazmi et al. (2023). Their research underscores the importance of identifying the most effective fabrication techniques.

Vacuum Bagging
Garschke et al. (2012), for instance, demonstrated that quality laminates, comparable to autoclave panels, could be achieved by merely adjusting the vacuum bagging setup and pressure. This finding suggests that modifications to existing processes can yield significant improvements in product quality.

Heating Effects
Further, Plackett et al. (2003) concluded that heating during the manufacturing process led to a noticeable increase in the tensile strength of PLA composites. This was attributed to the rapid removal of moisture and air from the natural fibres due to heat exposure, which underscores the importance of process parameters in determining composite properties.

Infusion Techniques
Exploring different infusion techniques, Qi et al. (1999) put forth resin film infusion as a cost-effective technique for composite fabrication. This method’s efficacy was later confirmed by Kogan et al. (2012), who found that it provided mechanical properties on par with those obtained through conventional Prepreg Autoclave technology.

3.26

Production Focus

Narrowing **Methods**

In light of the research findings discussed and the established design parameters from Phase 1 and Phase 2 for composite design, it is reasonable to exclude certain manufacturing techniques.

This allows for a narrower focus on the following methods:

1. Film Stacking / Resin Film Infusion
2. Diaphragm Forming
3. Thermoforming
4. Resin Transfer Moulding
   - Vacuum Assisted Resin Transfer (VARTM)
   - Vacuum Bagging
   - Resin Infusion Moulding (SCRIMP)

Film Stacking/ Resin Film Infusion
This method involves stacking/layering resin films between sheets of fibrous reinforcement. The entire stack is then subjected to heat and pressure, causing the resin to melt, flow and impregnate the reinforcement, forming a consolidated sheet of composite.

Studies by Le Duigou et al. (2009) and Jia et al. (2014) describe the film stacking procedure referred to by author and also concluded that film-stacking followed by hot pressing was a suitable method for producing PLA fibre embedded composites of varying fibre content, as the matrix impregnation is key in this method.

Diaphragm Forming
Diaphragm forming, as detailed by Okine (1989), includes enclosing a composite workpiece within two adaptable diaphragms, then applying heat and pressure. In the context of continuous fiber composites, the workpiece can move within the diaphragms to minimise wrinkling. This method effectively shapes simple forms and can manage more complex ones when extensible sheets are used.

However, it requires materials to be exposed to the glass transition temperature of the thermoplastic matrices, and this can extend cycle times, although methods to decrease them have been explored.

Thermoforming
Thermoforming has a direct impact on the mechanical performance of the composite. This method is usually employed for thermoplastic composites.

The outcomes of thermoplastic fabrication techniques or thermoforming depend on factors like temperature, pressure and dwell times.
In this process, a material is heated till the glass transition temperature for forming a specific shape in a mould (Dobah et al., 2020)

Resin Transfer Moulding (RTM)
RTM is a low-pressure moulding process for high-performance composites.
The fibre preform is placed in a closed mould, and the resin is injected under pressure to impregnate the preform. RTM allows for producing large, complex shapes with high fibre volumes and low void content (Merhi, 2022). The following are variations recorded in Resin Transfer Moulding:

Vacuum Assisted Resin Transfer Moulding (VARTM)
VARTM is a composite manufacturing process where a vacuum is used to draw resin into a dry fibre preform placed in a mould. The vacuum pressure helps distribute the resin uniformly throughout the preform, ensuring complete wetting of the fibres (Merhi, 2022).

Vacuum Bagging
According to Kazmi et al. in 2023, vacuum bagging is a process that applies mechanical pressure to a laminate during curing. First, materials are placed in a mould and sealed in a vacuum bag. Then, atmospheric pressure is applied to provide uniform pressure on the laminate, which helps to consolidate and cure it within a specific temperature profile.

Resin Infusion Moulding (SCRIMP)
SCRIMP is a VARTM technique that utilises a distribution medium to improve resin flow, making it ideal for larger structures. This method also allows for better control of the fibre/resin ratio, resulting in a uniform, high-quality composite. (Source: MIT OpenCourseWare, 2003).

3.27

Workplan & Strategy

Research **Focus**

This study aims to employ circular production methods to fabricate entirely biobased, geometrically shaped flax-PLA composites.

“The forming method used, in general, determines the cost to produce and the quality of the part” (Okine, 1989, p.52).

As informed by prior research, these potential production methods present a clear pathway towards developing a cost-effective alternative to popular manufacturing techniques.

Strategy: **Reshaping**

The goal is to devise a method suitable for small-scale production at reduced capital costs, using a reshaping technique currently underutilised in the composites manufacturing industry.

The strategy is to leverage vacuum, pressure, and heat to achieve the desired properties through a simplified, circular process to consolidate and shape sheet biocomposites.

Reshaping, as a technique, will preserve the structural integrity of the composite while allowing structural reuse as a strategy at the end of the primary use case.

Evaluation
Initially, the manufactured composites will be designed for structural components.
Then, based on their performance post-use and reshaping, they may be further developed for use as secondary structural components.

Experimental **Details**

The upcoming chapter, “Design of Experiments,” will focus on different manufacturing methods and their impact on the final properties of composite designs.

The chapter will also explore these methods’ skill, cost, energy and production time implications.

Selected Methods
The chosen manufacturing techniques will be tested based on the working principles of four industrially employed manufacturing techniques in conjunction with the compatibility with specific PLA mediums, namely film and polyol resin.

These techniques will include :

1. **resin infusion & vacuum forming;**
2. **film stacking & compression moulding.**

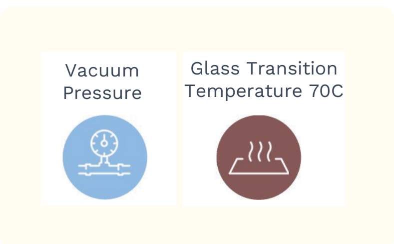
Evaluation
Investigating this manufacturing technique will show how effectively it uses the materials to produce fully biodegradable composites.

The resulting composites should have minimal residual stress, dimensional accuracy, shape conformance, and dense consolidation.

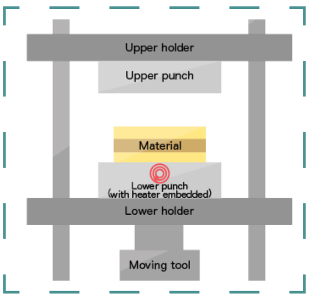
Parameter Study
Subsequent experiments will examine the fabrication, as well as the shaping and reshaping of the consolidated composite.

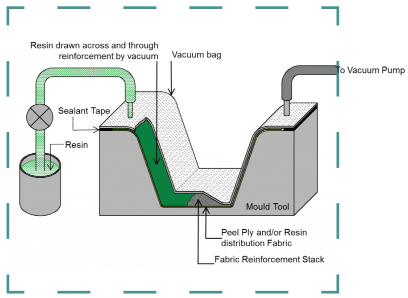
The aim is to identify the precise processing parameters (temperature and pressure profiles) and fibre-polymer ratio to meet the **structural reuse criteria** for the composites.

Parameters Chosen



Methods Chosen





Summary

The chapter comprehensively explores composite materials, focusing on the engineering and design process.

It underscores the importance of a four-phase iterative process in developing biodegradable composites, emphasizing the need to carefully select constituents, laminate design, manufacturing process, and structural analysis.

Each phase is interconnected, requiring adjustments based on the outcomes of the subsequent steps, highlighting the complexity and precision involved in composite design.

The choice of twill weave for flax composite is particularly intriguing, demonstrating how material selection goes beyond mechanical properties to include factors like drapability, aesthetic appeal, and yarn crimp.

Reinforcing that material engineering decision are multifaceted, balancing functional requirements with aesthetic and practical considerations.

The exploration of flax-PLA composites brings to light the potential of sustainable materials in engineering applications.

The chapter emphasizes the need to understand these composites' thermal stability and long-term behaviour, reminding us that adopting sustainable materials requires thorough investigation and understanding.

Overall, the chapter provides a reflective insight into the complexities of composite design and the potential of sustainable materials, emphasizing the need for a meticulous, iterative approach and a deep understanding of material properties.

04

empirical study
design of **experiments**

This chapter will document the **experiments** and **outcomes** of the **biocomposite** engineering to validate the criteria and hypothesis as designed.

4.1

System Design

I Structural Criteria **Objective**

This study aims to engineer a biocomposite for use in a circular cladding panel, i.e., a structural facade part.

Therefore, it is crucial to define the structural criteria grounded in both — a specific case study and a universal protocol to create a material suitable for facade application and potential for structural reuse.

Furthermore, this approach allows for establishing real-world context, usage and reuse limitations, and an understanding of the material's behaviour as a panel.

II Phase **Synthesis**

The culmination of the insights gained from Phase 1, Phase 2, and Phase 3 provides us with a comprehensive toolkit to design the optimal biocomposite.

From these phases, we have derived the following:

- Twill Woven Flax Fabric,
- PLA film and Polyol Resin
- Standard sequencing and configuration for the sheet material,
- Refined list of manufacturing methods compatible with our chosen materials, mediums, and desired quality.

The manufacturing process will adhere to standard procedures validated by widely cited literature, as the validated research will mitigate the influence of unique methods on the final measurements.

III Contextual **Relevance**

Including a case study in our research offers a practical, real-world perspective on developing our biocomposite.

The selection of a specific facade cladding case was made considering its potential for emulation using our biocomposite material and its suitability for demonstrating our proposed circularity strategy of reshaping.

In addition, the case study provides tangible parameters for design and performance, further grounding our research in practical application.

IV Part **Geometry**

The chosen facade design is characterized by specific geometric attributes that present unique challenges and opportunities for our biocomposite.

By reproducing this part geometry, we will showcase the material's versatility and potential to adapt to complex architectural requirements.

Furthermore, reshaping our biocomposite to fit this design allows us to evaluate its potential for reusability, a significant aspect of our circularity strategy.

V Role of **Design Calculations**

FEA plays a crucial role in predicting the behaviour of our biocomposite under various loads and conditions. We can anticipate the material's performance in real-world situations by inputting our experimental test data into FEA simulations and refining our design and manufacturing processes accordingly.

VI Facade **Checklist** & Parameter **Selection**

A comprehensive facade performance checklist, provided by **Scheldebouw, Permasteelisa** offers a variety of parameters against which we can evaluate our biocomposite.
However, given the scope of our thesis and the specifics of our case study, only certain parameters from this checklist have been selected for testing.

Furthermore, the chosen parameters align most closely with the performance requirements of our case study and the broader goals of our research, ensuring that our biocomposite is tested against the most relevant criteria.

VII Testing & Hypothesis **Validation**

To gauge the material's suitability as the case panel, we will follow ASTM protocols to test mechanical properties at room temperature before and after reshaping.

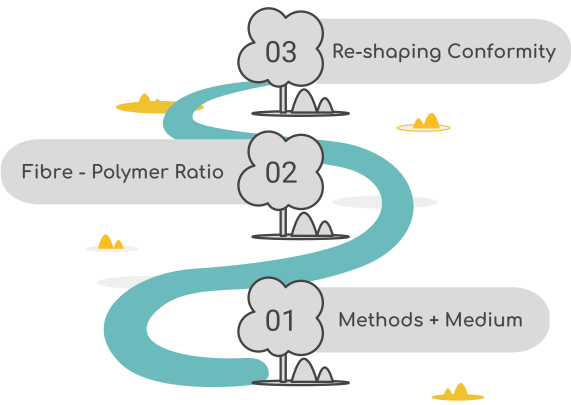
This testing serves as a proof of concept, justifying our structural reuse strategy and shedding light on the reshaping process's impact on the biocomposite's mechanical behaviour.

4.2

Design of Experiments

Experimental **Roadmap**

This chapter will present the design of three experimental studies conducted on the biocomposite design, and their outcomes, as part of this research:



Experiment **One**

This experiment compares the effectiveness of two production techniques (VARTM & Hot Pressing) and two different mediums (Film & Polyol) of Poly-lactic Acid (PLA) in the manufacturing of the bio-composite.

The experiment is to determine whether one combination of method and medium yields superior results over the other, thereby optimizing the bio-composite manufacturing process.

Experiment **Two**

Building on the findings of Experiment 1, the second experiment aims to follow up on the production process with a second cycle of manufacturing.

This attempt will examine the resulting differences in appearance, texture, time & energy requirements for maximum consolidation when manufacturing different Flax-PLA mass ratios with varying levels of flax laminae.

Experiment **Three**

The final experiment in this series will use specimens from Experiment 2 to investigate the feasibility and effects of a novel bio-composite reshaping strategy.

The outcomes will determine practicability of the strategy used, shape conformity of biocomposite & impact of reshaping on the material.

Hypotheses

Experiment 1 Hypothesis:

Which method-medium combination (Pair 1: Hot Pressing and PLA Film; Pair 2 : VARTM with PLA Polyol Resin) yields a better sheet material in terms of consolidation, time, cost, skill required, and quality achieved, compared to using?

Experiment 2 Hypothesis:

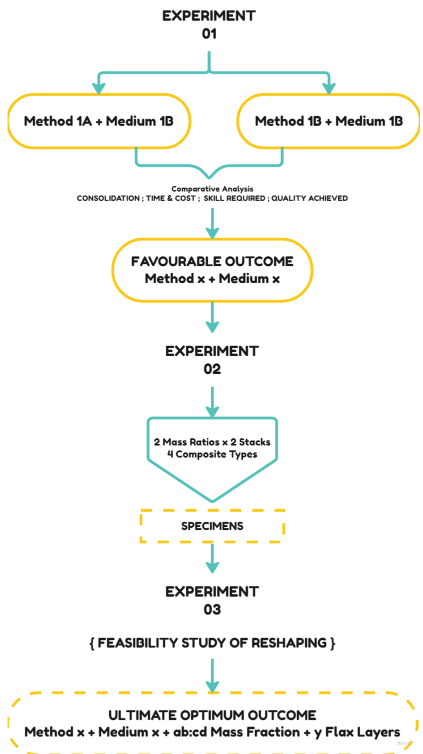
Do variations in Flax-PLA mass ratios and fibre lamina ply levels significantly influence the selected production processing & resultant composite traits including appearance, texture, and energy demand for optimal consolidation?

Experiment 3 Hypothesis:

Is the proposed reshaping strategy for bio-composites feasible, and if so, what is the level of mould conformity, time and energy expenditures, and characteristics such as texture, appearance for each specimen type?

Testing Post Experiments:

Is there a difference in mechanical properties of the biocomposite before and after reshaping?



4.3

Design of Experiment 1

Objective

The goal of the experiment is to investigate the effect of different production techniques and PLA mediums on the Manufacturing of the Biocomposite. The specific outcomes of interest are time, cost, skills required and quality of sheet consolidation.

Factors

The experiment has two factors:

Factor 1 **Mediums**

As discussed in Matrix Selection in this study earlier, **Film and Polyol Resin** emerged as the most compatible mediums to fabricate a sheet of Flax PLA composite. This factor has two levels:

1. PLA Film 0,30 um from Bleher
2. PLA Polyol BioPhotopolymer Resin from eSun

Factor 2 **Methods**

Two out of the selected manufacturing techniques from the Phase 3 of Composite Design were compatible with specified PLA Film and Polyol Resin. Therefore, this factor has two levels:

1. Vacuum-assisted Resin Infusion (VARI)
2. Resin Film Infusion (Temp-Pressure Profile)

Settings

Settings refer to the specific combinations or pairings the levels from factors can take. In this experiment, each PLA medium is specific to a production technique. There are two settings given the material-process constraint:

1. Polyol Resin is used with VARTM
2. Film is used with Resin Film Infusion

Responses

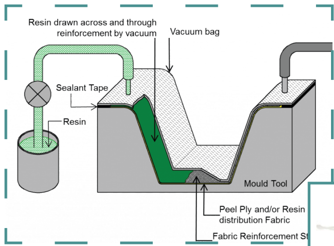
The responses of the experiment are the outcomes of interest - time, cost, skill required and quality of sheet consolidation achieved. These will be observed and recorded for each of the two settings.

Experimental Design

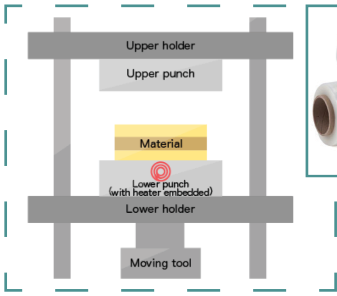
Given the fixed pairing, the experiment will involve a direct comparison between the two predetermined combinations: VARTM with Polyol Resin vs Hot Pressing with Film.

Cause & Effect Link

By analyzing responses (time, cost, quality) for each factor setting (method-medium pairs), the goal is to identify the optimum manufacturing & medium pair that yields best results, hence streamlining the process.



VARTM with Polyol Resin



Resin Film Infusion with Film

DoE Glossary For Reference

Factor: An input variable that is manipulated in an experiment to observe its influence on the response.

Levels: The different settings or values of a factor that are used in an experiment.

Settings: The specific combinations of factor levels that are chosen for conducting an experiment.

Response: The output variable(s) that is measured in an experiment. It is what we want to predict or optimize based on the levels of factors.

Experimental Design:
The process of planning an experiment to ensure that the data obtained enables effective decision-making.

Cause-and-Effect Relationship:
The relationship that is established when changes in one or more factors (the causes) lead to changes in one or more responses (the effects).

4.4

Experimental Setup 1A

Setup for **VARTM with Polyol & Flax**

The procedural steps for making a Flax-PLA composite with Polyol Resin consisted of specific equipment for Vacuum Assisted Resin Infusion and curing equipment for the UV sensitive Resin.

Kit of **Parts**

The assembling and set-up required the following:

Technical Flax Fabric
FLAXDRY-BL360 Twill 2x2 woven flax fabric from EcoTechnilin - 300 g/m² (NF G07-150) was used for the woven balanced reinforcement.
+ Fabric Scissors + Tape + Hot Iron

PLA Polyol BioPhotopolymer Resin

eSUN self-produced Synthesised PLA Polyol Bio-Photopolymer Reisn, cures at 395 nm UV light
Viscosity = 100-270 mPa/s Density = 1.07-1.10 g/cm3
+ Nitrile Gloves + UV Lamp + Mask

Vacuum Pump

Provided by the Think Lab at TU Delft under the supervision of Professor Mauro Overend & Lab Technician Hans Ginhoven.

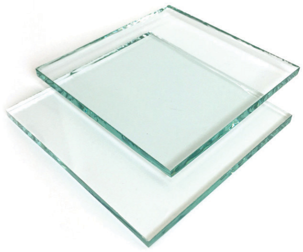
Resin Infusion Starter Kit

Retrived from Think Lab, TU Delft, consumbables sourced from Easy Composites, EU.

Professional Resin Catch Pot
Vacuum gauge and liners
2x Infusion Tube Line Clamp
2x Silicone Resin Infusion Connector
5m 6mm ID PVC Vacuum Hose
5m VB160 Vacuum Bagging Film (1.52m wide)
5m PP180 Peel-Ply
5m FM100 Resin Infusion Mesh
10m Resin Feed Spiral
2x 15m Roll Vacuum Bagging Sealant Tape
1m of 8mm ID Silicone Vacuum Hose

Mould Essentials

Plain Float Glass and Mould Release wax Provided by the Think Lab at TU Delft under the supervision of Lab Technician Hans Ginhoven.



4.5

Vacuum Assisted Resin Transfer

Procedural **Steps**

Step 1 Preparing the Mold
The glass sheet was cleaned of any particles, and layers of mold release wax was buffed on the surface of the glass for easy withdrawal after curing.

Step 2 Preparing the Flax Fabric
2 layers of 200 x 200 cm of Technical Twill Fabric was cut from a roll of flax fabric. The fibres were nominally ironed to remove any creases of wrinkles before layup. The layers were laid in an unidirectional sequence.

Step 3 Preparing for Resin Infusion
This step includes the peel-ply and the infusion mesh layup, however was skipped for the twill weave has reinforcement that guides resin to flow evenly through the fabric.

Step 4 Placing Feed Spirals and Connectors
The resin feed spiral was placed, with the silicon connectors positioned on the either ends, inlet was located over the feed spiral and the outlet was located on the opposite end.

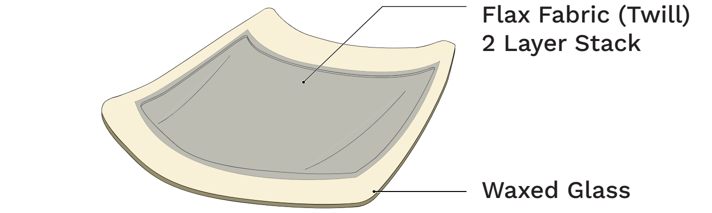
Step 5 Vacuum Bagging
A perimeter of vacuum sealant tape was created to place and seal the vacuum bagging film on it without any creases of gaps. The corners were pleated to ensure perfect seal.

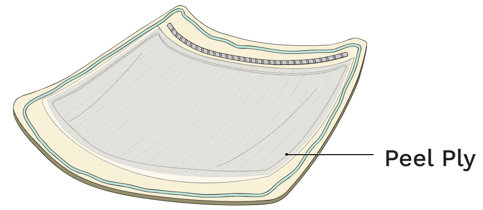
Step 6 Connecting Outlets
Next, the outlets were connected to the Resin Trap with the 6 mm PVC Feed Hose and further to the Vacuum Gauge & Pump with the 8 mm Silicone Vacuum Hose. The resin feed line was connected (clamped, without resin), all ends of the pipes were sealed with tape.

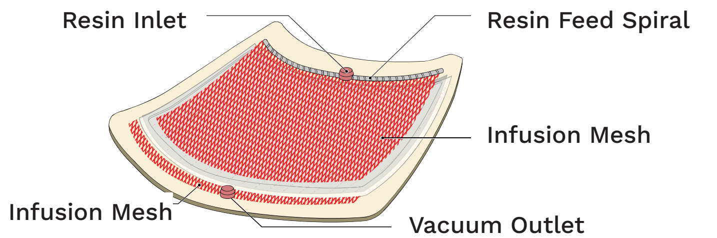
Step 7 Vacuum & Resin Introduction
The vacuum gauge was turned on and air was removed from the sealed setup. Once full vacuum was achieved, PLA Polyol Resin was introduced into the Feed Pot and Line Clamp was turned off.

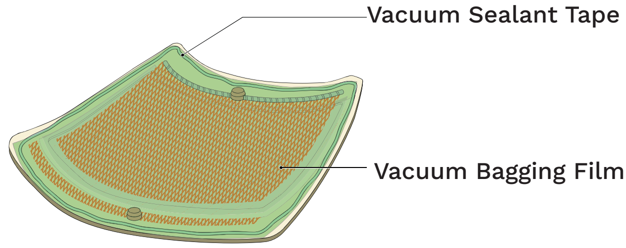
Step 8 Resin Infusion
The resin slowly flowed through the flax layup, while vacuum was maintained. Infusion was continued till resin had completely permeated the Fabric.

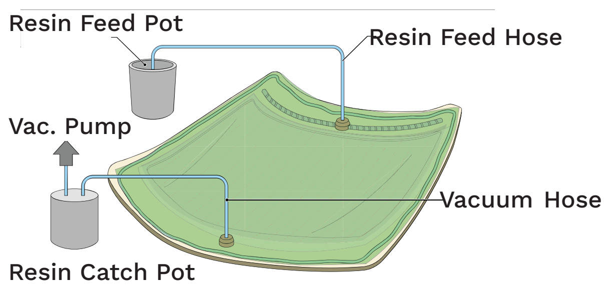
Step 9 Curing in UV (Room Temp)
Post infusion, the complete set up was exposed to UV lighttoinitatecuring.Thiswasaparticularstepas,Polyol Resin was biophotopolymeric and required UV curing. After curing for 24 hours, the setup was unsealed, and composite was taken out.

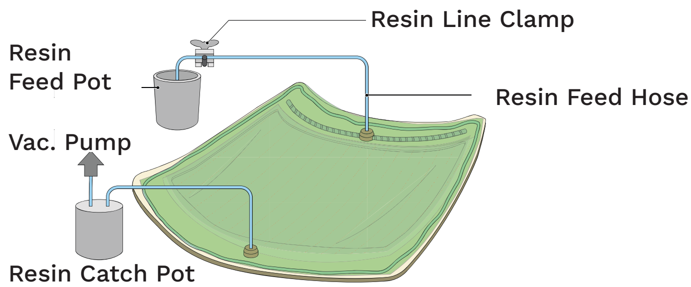










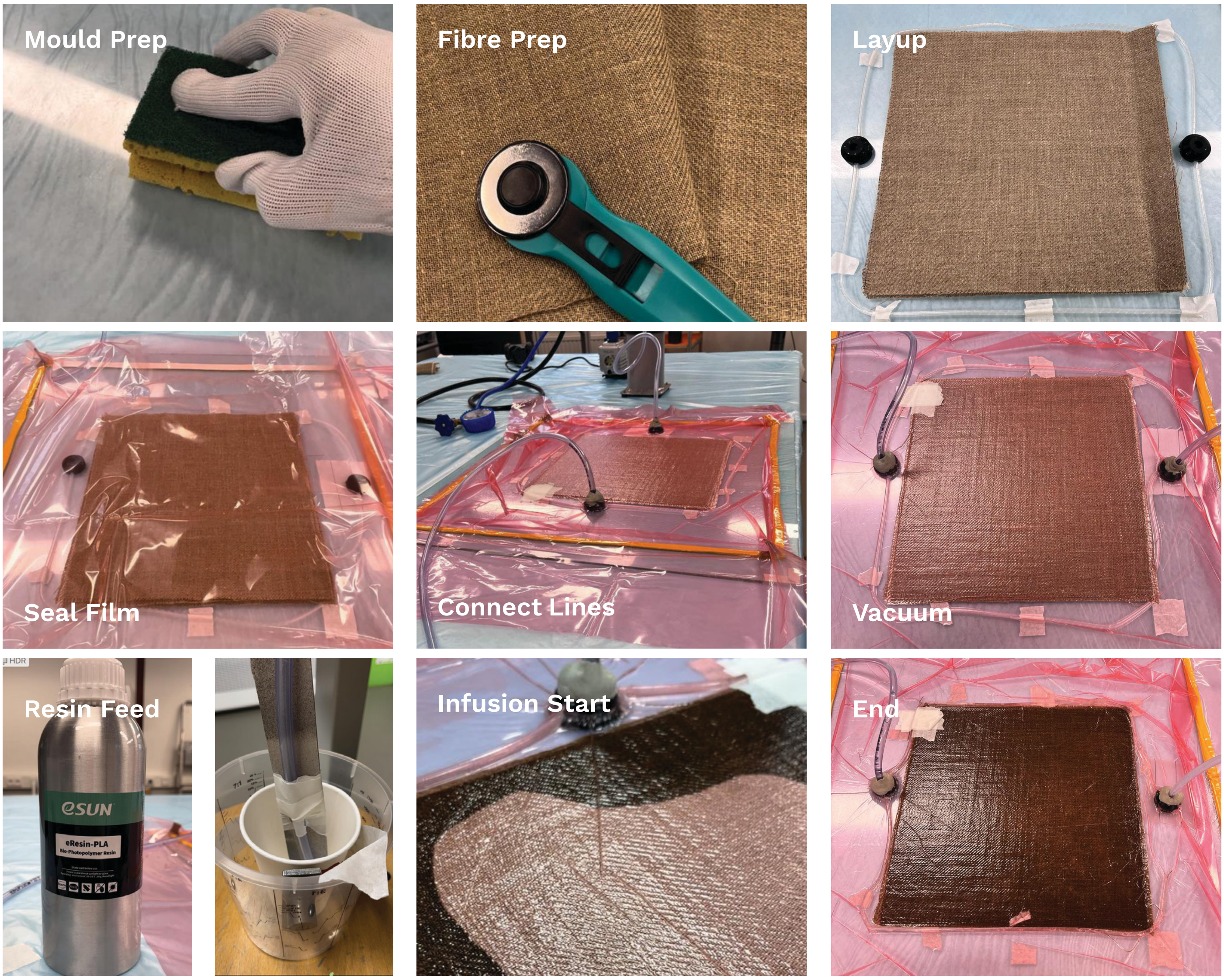


Location: Think Lab, TU Delft
Lab Temperature: 21.2 Deg C, Naturally Ventilated

4.6

Results (VARTM)

Process **Images**



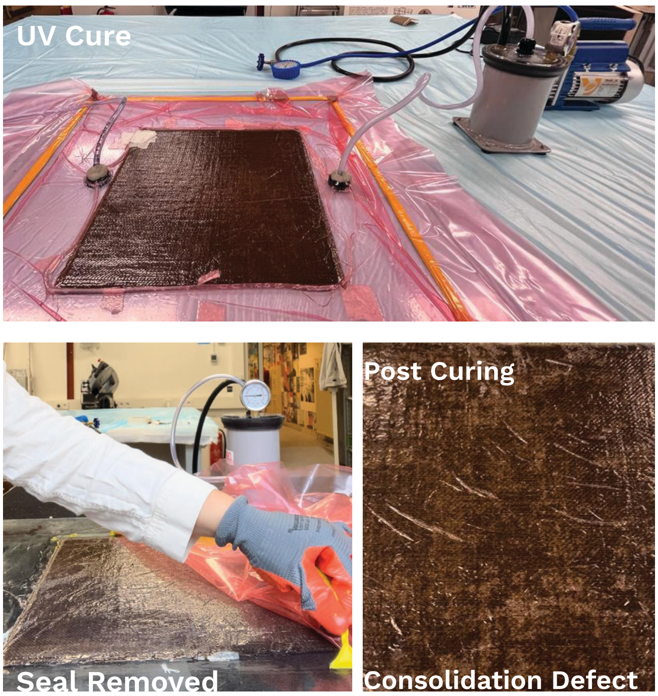
Findings & Observations

Curing / Consolidation
Curing took more than 24 hours of UV exposure with only surface level solidification of the resin. Consolidation was pure, as composite was still wet after 48 hours.

Quality Achieved
Quality achieved was poor, as it was not suitable to be a sheet material.

Texture, Appearance
Sticky, strong odour, wet texture, brittle.

Resources Consumed/Waste Generated
This method - medium pair generated waste & consumed a lot of time, skill, costs and resulted in a unsuccessful result, however, stronger vacuum and UV exposure can be tried.



4.7

Experimental Setup 1B

Setup for **Resin Film Infusion with Film & Flax**

For the setup of making a Flax-PLA composite with PLA Film, this research collaborated with NPSP, and conducted the Resin Film Infusion at the NPSP lab under the supervision of Mr Willem Bottger, Material Developement Director at NPSP, Amsterdam B.V. Mark Lepelaar from NPSP also guided with his expertise in Thermoplastics.

Kit of **Parts**

The assembling and set-up required the following:

Technical Flax Fabric
FLAXDRY-BL360 Twill 2x2 woven flax fabric from EcoTechnilin - 300 g/m² (NF G07-150) was cut in 160 mm x 220 mm Pieces for the woven balanced reinforcement + Fabric Scissors + Tape + Hot Iron

PLA Film 30 µm Resin
+ Film cutter
Bleher Folientechnik GmbH sent samples of their Optimont® PLA Film of thicknesses **30 µm & 50 µm.**

Yield	= 26.9 m²/kg
Tensile strength at break	= 65.5 N/mm² (MD)
Elastic Modulus	= 1910 N/mm² (MD)
Melting Point	= 155-170 °C
Glass Transition Temp	= 55-60 °C

Steel Mould Plates & Silicone Rubber Sheets

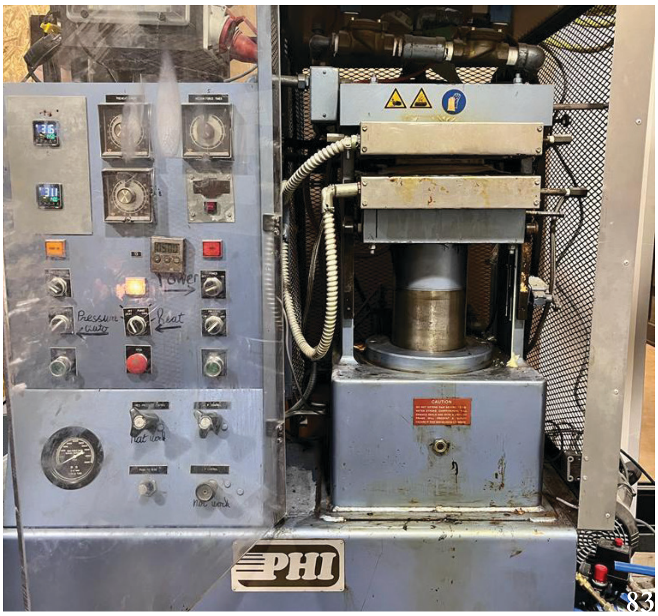
Provided by NPSP's Lab at Amsterdam.

Hydraulic **Press Machines**

The resin film infusion involved 2 machines, one for Heating the sequenced stack of PLA Film and Flax Fabric and the subsequent press for cold-pressing the layup at a certain temperarure. The idea was to melt the PLA at high temperature profile and consolidate the composite at room temperature and low pressure profile.

Hydraulic Press 1 Fontijne Holland 220KN Press
This press was used for heating the layup till 165 °C

Hydraulic Press 2 PHI Press
This press was used for cold-pressing the layup after.



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4.8

Resin Film Infusion

Manufacturing **Steps**

Step 1 Preparing the Mold
The steel plates by NPSP were cleaned and the silicone rubber sheets were cut to the size of the steel plates. The silicone sheets were to ensure a non-stick and heat resistant interface between the composite and the mould. Baking paper was also considered for a matte finish.

Step 2 Preparing the Flax Fabric
2 layers of 160 x 220 mm of Technical Twill Fabric was cut from a roll of flax fabric. The fibres were nominally ironed to remove any creases of wrinkles before layup. The layers were laid in an unidirectional sequence.

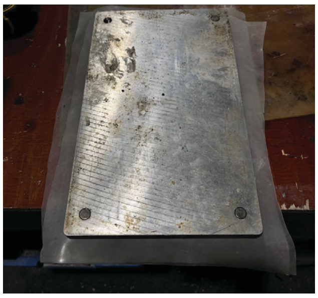
Step 3 Preparing the PLA Resin
26 layers of 160 x 220 mm of 30 um Film was cut from the PLA Film samples. The mass ratio between the Fibre: PLA was 70:30 for this attempt.
It was to validate the mass fraction suggested by Salman and coworkers (2008). These layers were laid in an unidirectional sequence as suggested earlier.

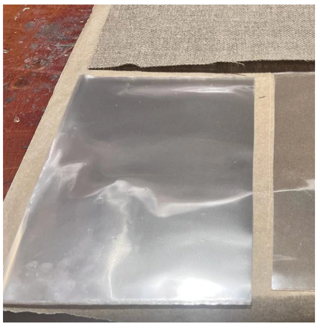
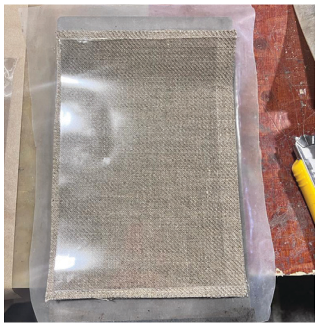
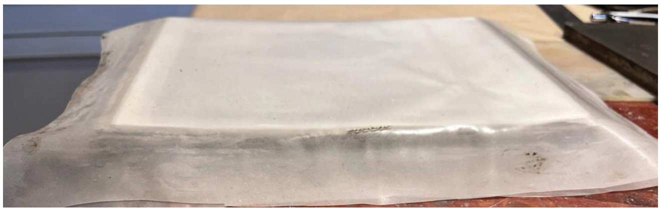
Step 3 Stacking the Layers in Mould + Silicone
10 layers of PLA was placed in the outermost sections of the layup, with 8 layers sandwiched between the 2 Flax Layers. Fibre Mass : Polymer Mass = 70 : 30. The entire stack was carefully transfered onto the silicone sheets + steel plate setup.
{ 10 PLA + 1 Flax **+ 8 PLA +** 1 Flax **+ 10 PLA }**

Step 4 Placing the Mould Plates in **Press** 1
The Press 1 was preheated till a temperature of till 165 °C. This temperature was the median temperature according to the TDS Data of the PLA Film.
The melting point would ensure the impregnation and flow of PLA into the Flax lamina. The composite within the steel plates were placed in contact with the heated press for 8 mins. TGA of PLA Film notes that the melting time for PLA is 8-10 mins (Kazmi et al., 2023).

Step 5 Placing the Mould Plates in **Press** 2
After 8 mins, the steel plates(+composite) is taken out of the hot press, and transferred to the PHI cold press at Room Temperature. A pressure of 2.5 T is introduced for 5 mins and the setting is set to auto. The cold pressing at nominal pressure would ensure even consolidation while the PLA cools in the stack.

Step 6 Remove from Press & Release Composite
After 5 mins of cold pressing, the plates were taken out and perfectly consolidated flax-PLA sheets were achieved.






4.9

Results (RFI)

Outcome Post Consolidation

4.10

Discussion of Results vs. 1A

Curing / Consolidation
The curing took less than 5 mins, under room temperature and pressure to result in 100% impregnation of PLA in fibres with near to perfect sheet consolidation. This was validated by result comparison with Kazmi et al. 2023 and Morales et al. 2017.

Quality Achieved
The desired quality of sheet material were achieved. As it was **a stiff, bendable, sheet like material, with considerable promise.** No odour, or handling issues.

Texture, Appearance
The appearance of natural flax fibres was achieved as PLA used was transparent. Texture of the 70:30 ratio was more fabric like with coarse tactility and texture of 60:40 samples were smoother to touch.

Resources Consumed/Waste Generated
This method - medium pair generated **Zero Waste** and no consumbles were required. All components of the production were reused and the machines ran at 8 min and 5 min intervals. Energy consumption is to be calculated. This method-medium pair resulted in a **successful biocomposite sheet consolidation.**

Comparisons with VARTM Experiment

Experiment 1A showcased different results. Curing required prolonged UV exposure of more than 24 hours, resulting in only surface-level solidification. The composite remained wet even after 48 hours, indicating inadequate consolidation.

The achieved quality was unsatisfactory, with the material not suitable to be in sheet form. The texture was sticky and wet, and the odour was strong, making handling difficult. Unlike the previous method, this one consumed substantial resources, generating waste and demanding more time, skill, and cost.

Experiment 1B proved to be more efficient and environmentally friendly, achieving the desired results with less time and resource expenditure. It produced a superior-quality composite compared to Experiment 1A. This comparison highlights the effectiveness of the methods used in Experiment 1B.

4.11

Updating the Hypothesis

Initial Hypothesis

Experiment 1:

Which method-medium combination (Pair 1: Hot Pressing and PLA Film; Pair 2 : VARTM with PLA Polyol Resin) yields a better sheet material in terms of consolidation, time, cost, skill required, and quality achieved, compared to using?

Ans: Most Effective Combination - PAIR 2

PLA Film + Resin Film Infusion in a Unique Temperature Pressure Profile

Observations
Resin Film Infusion with PLA Film was a better combination in all aspects.

Quality & Consolidation Achieved
RFI was Better, as VARTM and Polyol did not cure, and did not consolidated even after 24 + hours of safe range UV exposure.

Time, Cost, Skill Required
All parameters were low for RFI, as VARTM required excessive consumables and high skills to achieve a result. RFI did not generate waste, however VARTM generated a lot of polymer waste.

Updating Hypothesis Two

Do variations in Flax-PLA mass ratios and fibre lamina ply levels significantly influence the typical Resin Film Infusion process & resultant composite traits including appearance, texture, and time demand for optimal consolidation?

Note

This research carried out all material sampling at the same NPSP Laboratory Press, to prevent any batch irregularities / external influences on material due to manufacturing.

npsp

4.12
Design of Experiment 2

Objective

This experiment explores the variations in the production process, time requirements, and resulting composite characteristics (appearances, texture, time required for consolidation) when using different Flax-PLA mass ratios and varying levels of fibre lamina plies. In addition, the production technique and PLA medium used will be Resin Film Infusion, identified as most effective in Experiment 1.

Factors
In this experiment there are two factors:

Factor 1 **Flax-PLA Mass Ratio**
This factor has will take on two levels, the two different mass fractions of Fibre : Polymer

1. **70 % Flax : 30 % PLA**
2. **60 % Flax : 40 % PLA**

Factor 2 **No. of Flax Lamina**
This variation is for the number of Fabric Layers:

1. 4 Layers of Flax Fabric
2. 6 Layers of Flax Fabric

Settings

Settings refer to the specific combinations or pairings the levels from factors can take. In this experiment, due to the varying levels of fibre lamina and mass fractions. There are 4 settings :

473 4 Layers Flax ▯70 % Flax : 30 % PLA
673 6 Layers Flax ▯70 % Flax : 30 % PLA
464 4 Layers Flax ▯60 % Flax : 40 % PLA
664 6 Layers Flax ▯60 % Flax : 40 % PLA

Responses

The responses of the experiment are the observed outcomes - differences in production process, time requirements, appearances, texture, and time required for perfect consolidation. These will be observed and recorded for each of the settings.

Experimental Design

Given the factorial design, the experiment will involve involve testing all possible combinations of the mass ratios and fibre lamina plies.

4.13
Production Plan

General Features

Sample ID	Flax	PLA Resin	Panel Length (mm)	Panel Width (mm)
Comp 473	FLAXDRY BL360	OPTIMONT PLA 30 um	220	160
Comp 673	FLAXDRY BL360	OPTIMONT PLA 30 um	220	160
Comp 464	FLAXDRY BL360	OPTIMONT PLA 30 um	220	160
Comp 664	FLAXDRY BL360	OPTIMONT PLA 30 um	220	160

Number of Layers

Sample ID	Each layer Fibre Thickness (mm)	Each film Polymer Thickness (um)	No of Flax Layers	No of Polymer Layers	Total Fibre thickness (mm)	Total Polymer Thickness (mm)
Comp 473	0,83	30	4	56	3,32	1,68
Comp 673	0,83	30	6	82	4,98	2,46
Comp 464	0,83	30	4	88	3,32	2,64
Comp 664	0,83	30	6	130	4,98	3,9

Density & Yields

Sample ID	No of Flax Layers	No of Polymer Layers	Density of Fibre (g/cm^3)	Density of Polymer (g/cm3)	Areal Weight of Fabric (g/m2)	Yield of Fibres (m^2/kg)	Yield of Polymer (m^2/kg)
Comp 473	4	56	1,45	1,239	360	2,78	26,9
Comp 673	6	82	1,45	1,239	360	2,78	26,9
Comp 464	4	88	1,45	1,239	360	2,78	26,9
Comp 664	6	130	1,45	1,239	360	2,78	26,9

Mass Fractions

Sample ID	No of Flax Layers	No of Polymer Layers	Total Fibre thickness (mm)	Wt of Fibre (g)	Wt of Polymer (g)	Mass Fraction Fibre (%)	Mass Fraction Polymer (%)
Comp 473	4	56	3,32	169,45	73,279	70%	30%
Comp 673	6	82	4,98	254,18	107,301	70%	30%
Comp 464	4	88	3,32	169,45	115,152	60%	40%
Comp 664	6	130	4,98	254,18	170,112	60%	40%

Layup Arrangement

4 Layer Flax, 70:30 Ratio

--------	16 PLA
=======	1 Flax
--------	8 PLA
=======	1 Flax
--------	8 PLA
=======	1 Flax
--------	8 PLA
=======	1 Flax
--------	16 PLA

4 Layer Flax, 60:40 Ratio

--------	20 PLA
=======	1 Flax
--------	16 PLA
=======	1 Flax
--------	16 PLA
=======	1 Flax
--------	16 PLA
=======	1 Flax
--------	20 PLA

6 Layer Flax, 70:30 Ratio

--------	21 PLA
=======	1 Flax
--------	8 PLA
=======	1 Flax
--------	8 PLA
=======	1 Flax
--------	8 PLA
=======	1 Flax
--------	8 PLA
=======	1 Flax
--------	8 PLA
=======	1 Flax
--------	21 PLA

6 Layer Flax, 60:40 Ratio

--------	20 PLA
=======	1 Flax
--------	18 PLA
=======	1 Flax
--------	18 PLA
=======	1 Flax
--------	18 PLA
=======	1 Flax
--------	18 PLA
=======	1 Flax
--------	18 PLA
=======	1 Flax
--------	20 PLA

4.14

RFI for 473/673/664/464

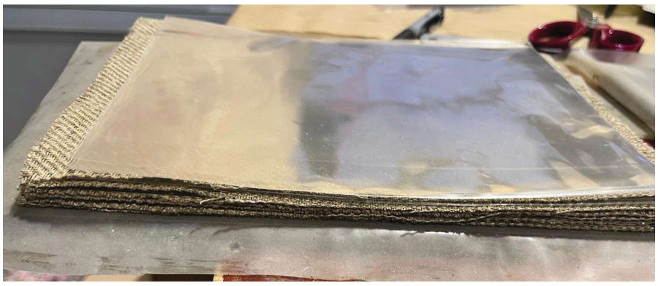
Manufacturing **Samples**

Step 1 Ensure clean mold & Silicone Sheet
Step 2 Prepare Flax Fabric

Composite 473 & 464
4 layers of 160 x 220 mm
Composite 673 & 664
6 layers of 160 x 220 mm of Technical Twill Fabric

Step 3 Preparing the PLA 30 um Film
Composite 473 - 56 layers of 160 x 200 mm
Composite 673 - 82 layers of 160 x 200 mm
Composite 464 - 88 layers of 160 x 200 mm
Composite 664 - 130 layers of 160 x 200 mm

Step 3 Stacking the Layers in Mould + Silicone as per the Layup Arrangement.



Step 4 Placing the Mould Plates in **Press 1**
The composite within the steel plates were placed in contact with the heated press at 165 °C. for 8 mins (70:30) & 12 mins (60:40).

Step 5 Placing the Mould Plates in **Press 2**
After 8/12 mins, a cold press with 2.5 T is in troduced for 5 mins and the pressure intervals is set to auto.

Step 6 Remove from Press & Release Composite
After 5 mins of cold pressing, the plates were taken out and perfectly consolidated flax-PLA sheets were achieved.

4.15

Outcomes

Consolidated Samples

Composite 473/ 70:30

Composite 464/ 60:40

Composite 673/ 70:30

Composite 464/ 60:40

Analysis

	Melt Time	Pressure	Texture
473	8 min	2.5 T	Coarse
673	8 min	5 T	Smooth
464	10 min	2.5 T	Coarse
664	12 min	5 T	Smooth

4.16

Discussion of Results

Initial Hypothesis
Experiment 2:

Do variations in Flax-PLA mass ratios and fibre lamina ply levels significantly influence the typical Resin Film Infusion process & resultant composite traits including appearance, texture, and time demand for optimal consolidation?

Cause & Effect Links
Melting Time Required

Sample ID 473, 673 8 minutes of melting time.
Sample ID 464, 664 12 minutes of melting time.

Higher Mass Ratios with more Polymer content needed a higher melt times, there was no link or difference seen due to flax layers.

Pressure for Consolidation

Sample ID 673 , 664 5 Tons
Sample ID 464, 473 2,5 Tons

Samples with more flax layers required a higher degree of pressure, while mass ratios did not show differentiation. Consolidation was measured by appearance and colour.

Texture Achieved

Sample ID 473 , 673 Coarse
Sample ID 464 , 664 Smooth

These findings suggest a potential relationship between the Flax-PLA mass ratios and fibre lamina ply levels with the achieved texture of the composite. As with more PLA, there is an increase in surface smoothness, while less PLA content exposes the Fibres.

4.17

Design of Experiment 3

Objective

The goal of this experiment is to determine whether a novel bio-composite reshaping strategy is feasible and, if so, to understand its effects on reshaped specimens in terms of mould conformity, time and energy requirements, level of bend acquired, and changes in appearance, texture, quality, and tensile and flexural strengths.

Specimen Layout

To understand its effects on the biocomposites, as per ASTM protocol. Tensile and Flexural Tests have different specimen measurements. This will be detailed in the next section. Each composite sheet of 160 x 220 mm was cut into 8 specimens :

4 **specimens** for **Tensile** Testing (a to d)
4 **Specimens** for **Flexural** Testing (a to d)

Factors

Main factor- **The Reshaping Strategy**;
as it is applied to the specimens chosen, across 473, 673, 464 and 664.

Settings

The settings of this experiment involve the reshaping cycles applied to the specimens. Each of the eight selected specimens will undergo two reshaping cycles.

(2x) 473- d Tensile & Flexural Specimen
(2x) 673- d Tensile & Flexural Specimen
(2x) 464- d Tensile & Flexural Specimen
(2x) 664- d Tensile & Flexural Specimen

Responses

The responses of the experiment are the observed outcomes - differences in production process, time requirements, appearances, texture, and time required for perfect consolidation. These will be observed and recorded for each of the settings.

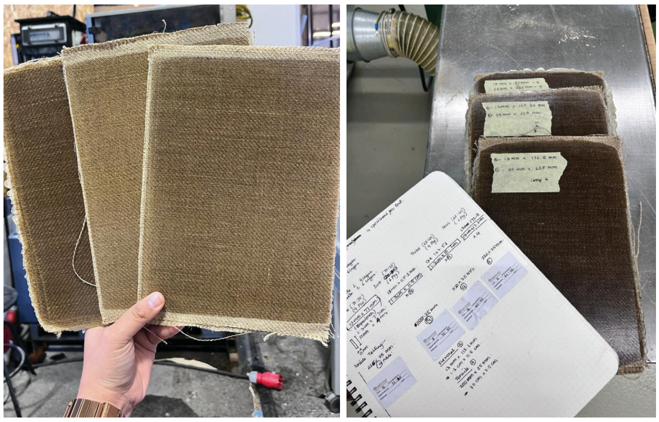
Experimental Design

Given the factorial design, the experiment will involve involve testing all possible combinations of the mass ratios and fibre lamina plies.

4.18

Specimen Preparation

Sheets to Specimens



Measurements

The thicknesses of the composites were measured with a vernier calliper. All four corners were noted down to take an average of the composites.

+	corner 1	corner 2	corner 3	corner 4	Avg (mm)
473	2.02	2.01	2.00	2.01	**2.01**
673	3.05	3.08	3.00	3.03	**3.04**
464	2.60	2.80	2.80	3.00	**2.80**
664	4.60	4.50	4.60	4.30	**4.475**

Flexural Test (3-Pt bending test) Specimens

The thickness of each composite influenced the length and the width of the flexural specimens to be cut. According to **ASTM Code D7264**

- **Width of Specimen** = **13 mm**
- **Test Span** = **32 * Thickness**
- **Length of Specimen** = **1.2 * Test Span**

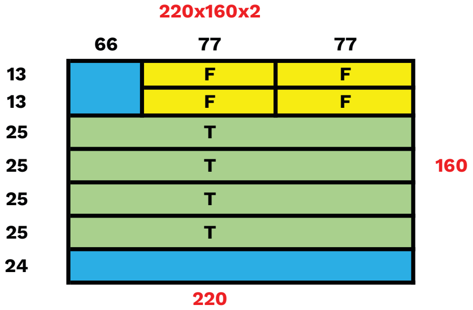
Tensile Test Specimens

The thickness of each composite influenced the length and the width of the tensile specimens. According to **ASTM Code D3039**

- **Width of Specimen** = **25 mm**
- **Length of Specimen** = **250 mm**

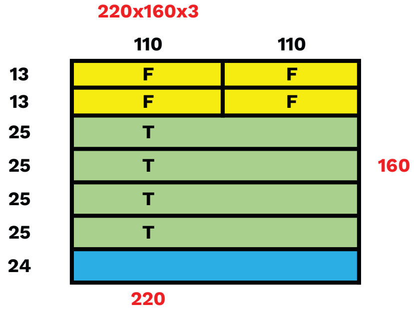
4.19

Machining Layout & Calculations



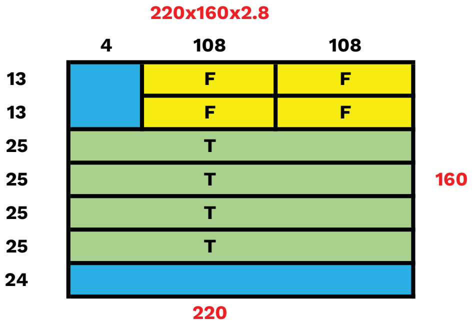
Type 473

Flexural 4 No.s 77 x 13 x 2,0
Tensile 4 No.s 220 x 25 x 2,0
Residual 1 No.s 66 x 26 x 2,0
Residual 1 No.s 220 x 24 x 2,0



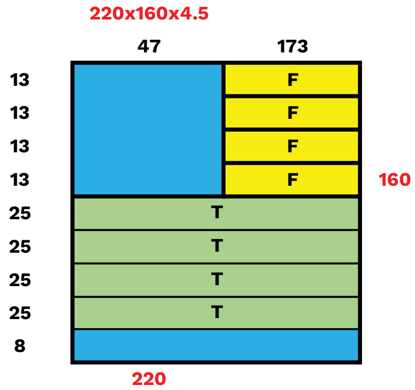
Type 673

Flexural 4 No.s 110 x 13 x 3,0
Tensile 4 No.s 220 x 25 x 3,0
Residual 1 No.s 220 x 24 x 3,0



Type 473

Flexural 4 No.s 108 x 13 x 2,8
Tensile 4 No.s 220 x 25 x 2,8
Residual 1 No. 4 x 26 x 2,8
Residual 1 No. 220 x 24 x 2,8



Type 673

Flexural 4 No.s 110 x 13 x 4,5
Tensile 4 No.s 220 x 25 x 4,5
Residual 1 No. 47 x 52 x 4,5
Residual 1 No. 220 x 8 x 4,5

Summary of Test Results of Composite Test Specimens										Summary of Test Result after Re-Forming			
Composite Type	Flax Layer	Fibre-Polymer Ratio	Sample ID	Thickness mm	Density kg/m2	Tensile Strength MPa	Young's Modulus GPa	Elongation at Break %	Flexural Strength	Tensile Strength MPa	Young's Modulus GPa	Elongation at Break %	Flexural Strength
Comp#1	4	70-30	C473-a	2,0	6,0	90	6,0	2,0	59,4	72	4,8	1,6	47,52
			C473-b	2,0	6,0	90	6,0	2,0	59,4	72	4,8	1,6	47,52
			C473-c	2,0	6,0	90	6,0	2,0	59,4	72	4,8	1,6	47,52
			C473-d	2,0	6,0	90	6,0	2,0	59,4	72	4,8	1,6	47,52
Comp#2	6	70-30	C673-a	3,2	9,0	113	7,5	2,0	74,3	90	6,0	1,6	59,4
			C673-b	3,2	9,0	113	7,5	2,0	74,3	90	6,0	1,6	59,4
			C673-c	3,2	9,0	113	7,5	2,0	74,3	90	6,0	1,6	59,4
			C673-d	3,2	9,0	113	7,5	2,0	74,3	90	6,0	1,6	59,4
Comp#3	4	60-40	C464-a	2,8	7,0	105	7,0	2,0	69,3	84	5,6	1,6	55,4
			C464-b	2,8	7,0	105	7,0	2,0	69,3	84	5,6	1,6	55,4
			C464-c	2,8	7,0	105	7,0	2,0	69,3	84	5,6	1,6	55,4
			C464-d	2,8	7,0	105	7,0	2,0	69,3	84	5,6	1,6	55,4
Comp#4	6	60-40	C664-a	4,5	11,0	135	9,0	2,0	89,1	108	7,2	1,6	71,3
			C664-b	4,5	11,0	135	9,0	2,0	89,1	108	7,2	1,6	71,3
			C664-c	4,5	11,0	135	9,0	2,0	89,1	108	7,2	1,6	71,3
			C664-d	4,5	11,0	135	9,0	2,0	89,1	108	7,2	1,6	71,3

4.20

Cutting Sheets

Machining Specimens

The rigid composite sheets were cut at the Model Hall, Wood Workshop under the supervision of Chris. Laser beam cutting was not opted as the composites were PLA and heat would not give defined and clear edge definitions.

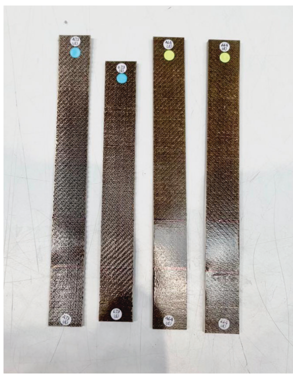
Tensile Specimens

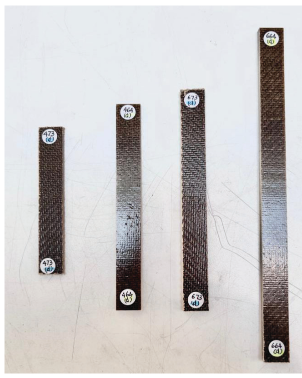
473 l = 250 mm w = 25 mm (a to d)
673 l = 225 mm w = 25 mm (a to d)
464 l = 250 mm w = 25 mm (a to d)
664 l = 250 mm w = 25 mm (a to d)

Flexure Specimens

473 l = 76,80 mm w = 13 mm (a to d)
673 l = 115,20 mm w = 13 mm (a to d)
464 l = 107,52 mm w = 13 mm (a to d)
664 l = 172,80 mm w = 13 mm (a to d)

Specimens (-d) for Reshaping





4.21

Case Study Overview

Case **Context**

The introduction of a case study in this research will illustrate the potential applications of the biocomposite and demonstrate its viability as a material for structural facade parts in a broader and practical context.

The Case - **MOL Headquarters, Hungary**

Nestled in the southern reaches of Budapest, the newly opened MOL Headquarters stands tall as the city's and the country's tallest building. Designed by Foster+Partners, the facade is realized by Permasteelisa Group, the MOL Headquarters is on track to achieving LEED Platinum and BREEAM Excellent certifications, optimizing its urban context to promote sustainability.

Selection **Rationale**

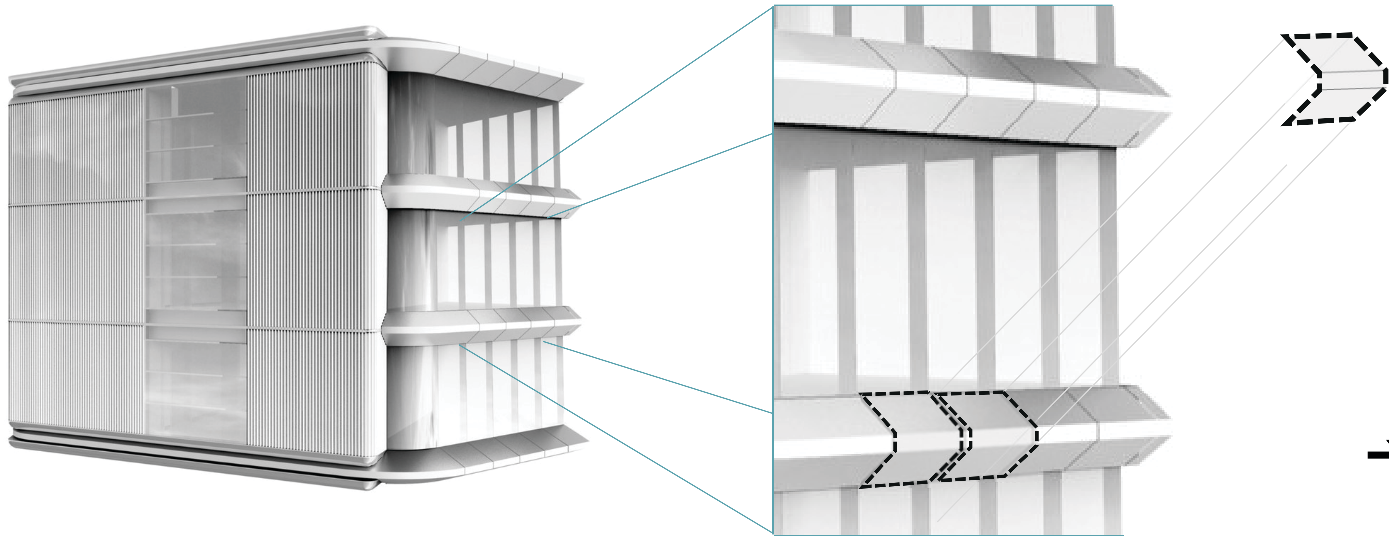
The MOL Headquarters was chosen for this study due to its architectural significance, its role as an icon of sustainable vision, and its facade design that provides an ideal platform to demonstrate the versatility of our biocomposite material. The complex facade design poses geometry that our biocomposite can emulate with developability, potentially setting new benchmarks for biocomposite use in architecture.

4.22

Facade Details

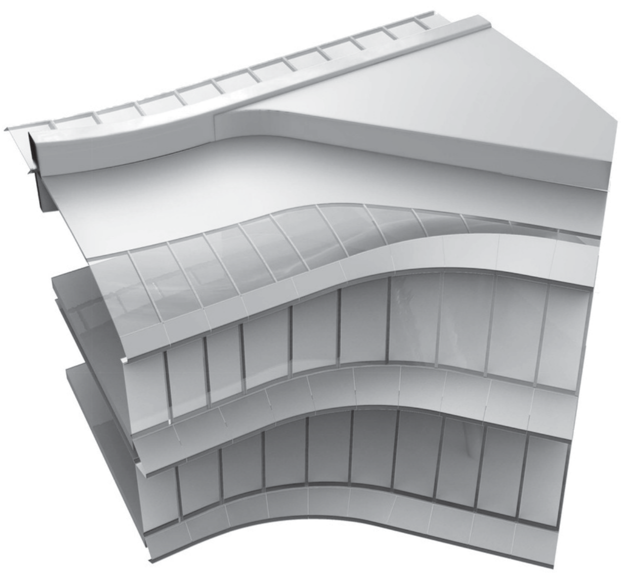
Facade **Details**

The facade is unitised and assembled on site, with floor-to-ceiling glass facade units and single curved 2D bullnose aluminium panels (3mm anodised aluminium sheet panels). These panels are assembled in the manufacturing factories in the Netherlands and are installed on site in Budapest. Each of these cladding panels had inbuilt gutter systems in the panels, which are not considered in the course of this research to simplify & focus on the geometry.



MOL Campus Cladding Mock-up
From Case Study Details - Scheldebouw

Part Geometry



Geometric **Details**

The building facade of the MOL Tower is an intricate ensemble of one-way curved and double-curved bullnose panels. These panels were optimized for digital fabrication of design and BIM teams.

The result is a complex facade form predominantly constructed from flat, easily manufactured panels, reserving the curve for only those places where truly necessary.

The panels' geometry aligned perfectly with this study's intent for finding the limits of biocomposite's geometric abilities. If biocomposite in development can emulate the bullnose curvature & design while retaining the ability to be flattened and reshaped, the findings shall present the facade innovation sector with biobased sheet material alternatives.

4. 23

Part Geometry & Strategy Principle

Geometry **Adaptation**

Inspired by the geometry of the MOL cladding, the following strategy is to adapt the design to accommodate the biocomposite under development. So, all complex profiles and connections are simplified, and this approach is not to exactly replicate, but aim for a modified version that both simulates the original design and highlights the biocomposite's potential.

Strategic **Techniques**

The proposed cycle of the biocomposite's use as a developable cladding panel is as follows:

1. Planar Biocomposite Sheetformed to Geometry

Initiating with a planar biocomposite sheet that is sheetformed with specific techniques to match the adapted geometry of the MOL Headquarters facade panels.

2. Reverting the Curved Panel to Flat Form

Upon reaching the end of its initial service life, the intent is to restore the contoured panel back to its planar form, demonstrating the biocomposite's reusability due to its capacity for multiple reshaping.

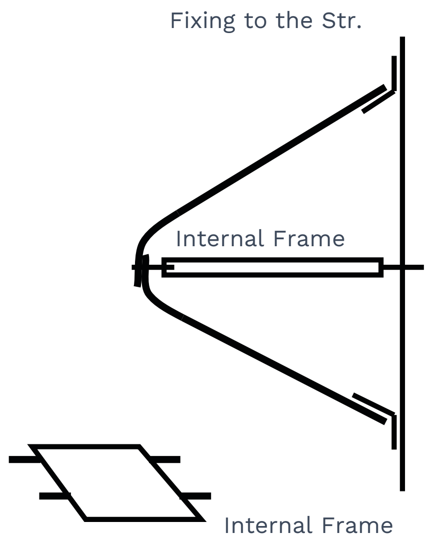
3. Inverting to Use the Unexposed Interior Facia

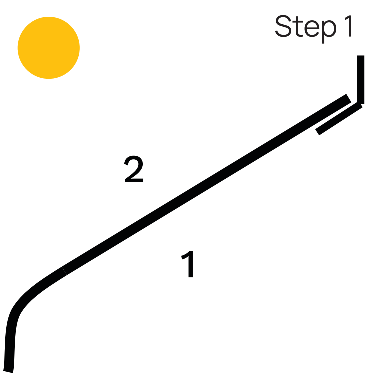
The exterior surface of a cladding panel inevitably experiences weathering effects such as moisture, temperature fluctuations, and UV exposure, which gradually degrade its strength.

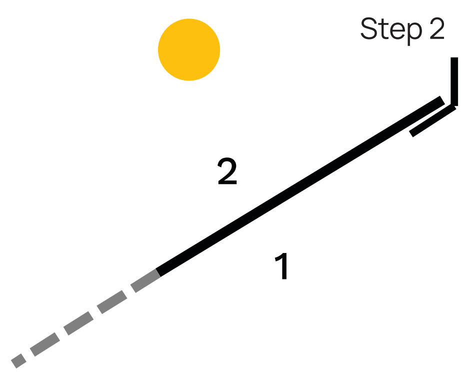
In contrast, the interior surface remains relatively sheltered from these harsh environmental conditions, thus retaining much of its original resilience.

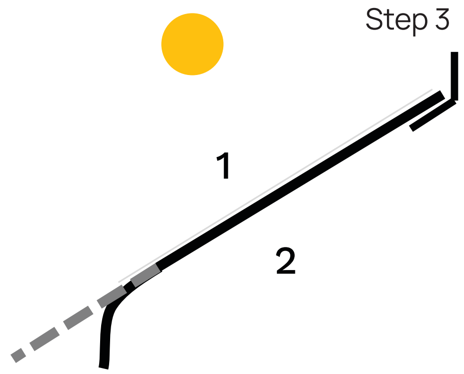
In the context of our case study, we hypothesize that the preserved strength of the panel's interior surface can be effectively utilized by reshaping the composite panel.

This approach leverages the unexposed interior surface's robustness, potentially extending the functional lifespan of the cladding panel and enhancing its sustainability









Vacuum **Thermoforming**

The biocomposite cladding panels begin their lifecycle as planar sheets. This initial form undergoes a transformation process known as vacuum thermoforming, where under vacuum pressure and at the transition temperature of the thermoplastic matrix, the sheet is shaped into a geometric form.

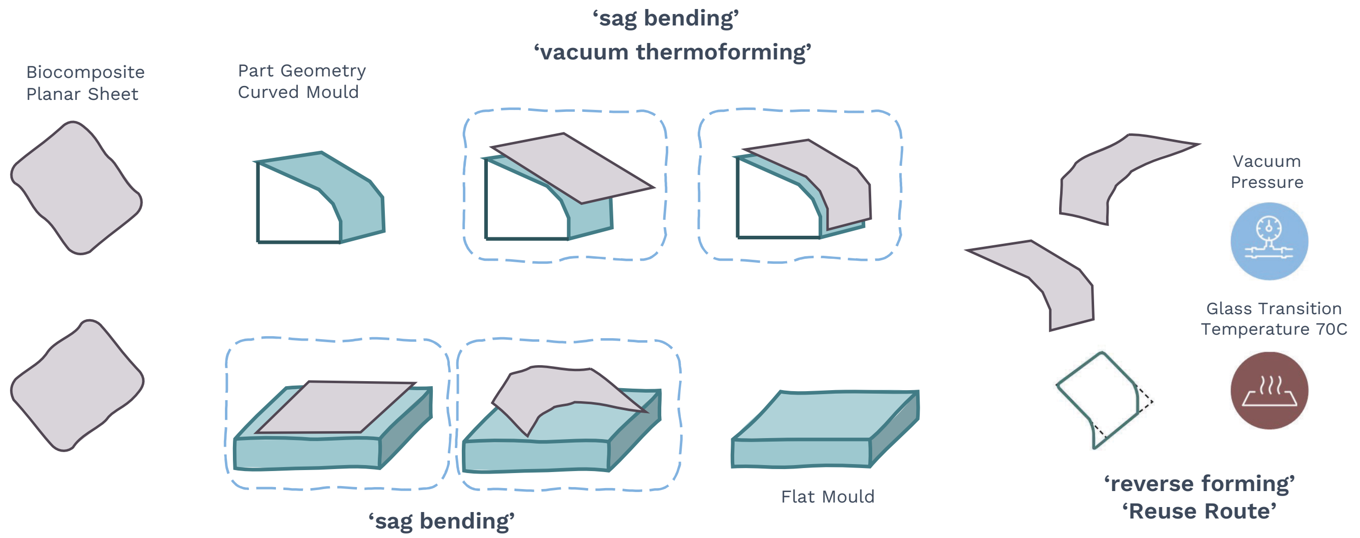
This process leverages the moldability of thermoplastics under heat and vacuum conditions, allowing for precise shaping that is integral to our design.

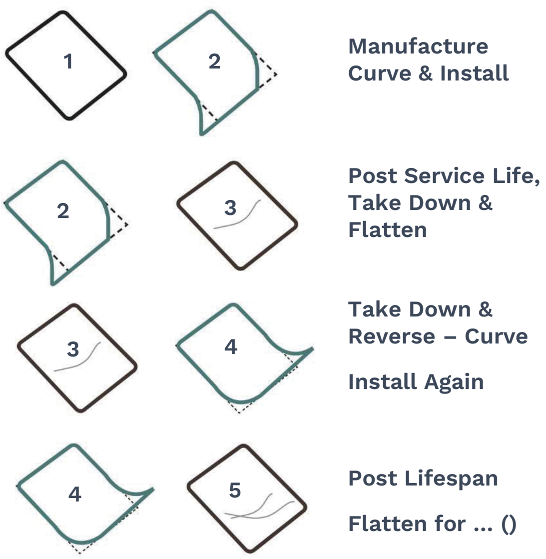
Reverse **Forming**

Post-production, these curved panels are installed to serve their intended purpose.

When the panels reach the end of their first design life, they can be flattend by sag bending on a planar mold to be restored to the original flat sheet. This technique emphasizes the capacity for reshaping.

The flattened panels can be reverse formed, underscoring the versatility of the biocomposite for potential reuse.





Circular **Re-Loop**

The entire reshaping process takes place under vacuum pressure and application of heat for glass transition, ensuring the maintenance of material integrity throughout each cycle.

The proposed loop of use illustrates its viability in a circular built environment within the AEC sector.

FIRST USE CYCLE
(Manufacture, Curve Install)

Post First Design Life

SECOND USE CYCLE
(Demount, Repair, Curve, Install)

Post Second Design Life

END OF SERVICE LIFE
(Both Facia exposed & affected)

4.24
Experimental Setup 3

Setup for **Novel Reshaping Stratgy**

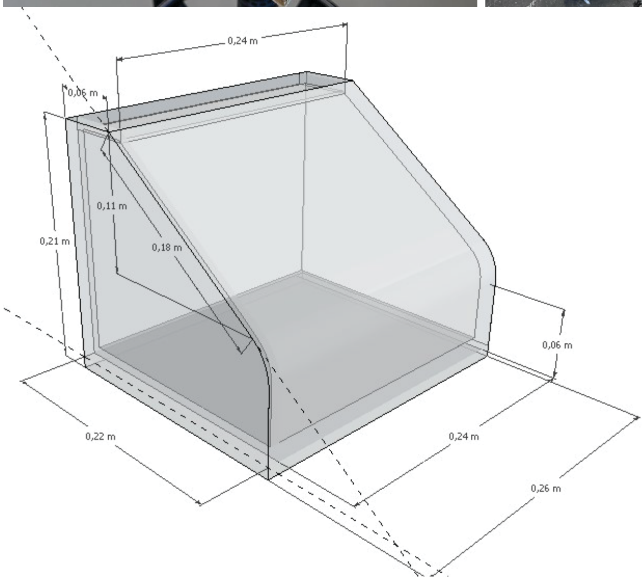
The main attempt of this experiment was to develop the re-usable mould for shaping the composite, and design the nescessary method that enables the shaping the composite in vacuum pressure and temperature profile .

Kit of **Parts**

The assembling and set-up required the following:

Recycled MDF + Wood Glue
1:4 scale model of the top panel for the case study was chosen for reproduction. This mould featured the closest tangential radii of curvature ~ 0,04 m instead of the sharp bends in the case geometry.
The angle of 36 ° was maintained. Taped & Glued.





“ a reshaping process with re-usable components that aims to integrate clean & circular processing methods in biocomposites ”

The vacuum + thermoforming set-up required the following:

Vacuum Bagging Setup + Vacuum Pump
For the vacuum element of this strategy all vacuum bagging essentials were required.
Silicone Vacuum Hose + VB160 Vacuum Bagging Film LFT + High Temperature Vacuum Sealent Tape + The Vacuum Pump as used earlier for VARTM

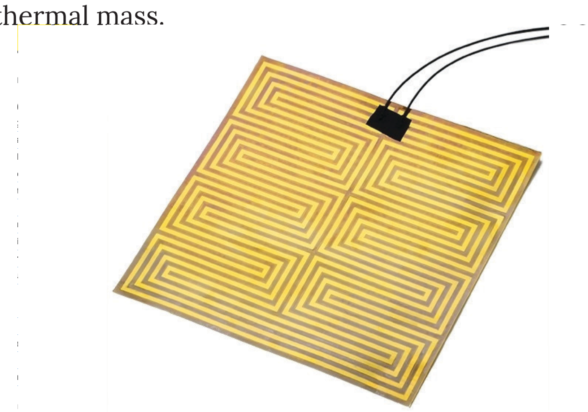



Thermal Setup + Power Supply

For the heating element of this strategya novel method was attempted. The idea was to source a **flexible interface** that could:

- **heat, cool, and not stick** to the composite.
- **conform to** all shapes/**curvatures subjected**

Among all options, a heating mat had the most potential as a flexible heat source, with minimal thermal mass.



23 x 23 cm 12 V 10 A Heating Mats were sourced from 123d.nl. Used in 3D printer heat beds, use of such a mat was **a novel experiment with biocomposites.**

4. 25

Vacuum Thermoforming

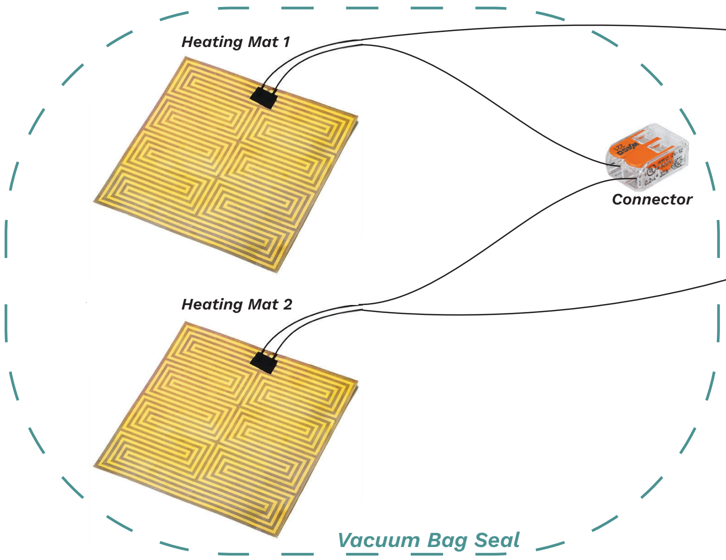
The **Procedure**

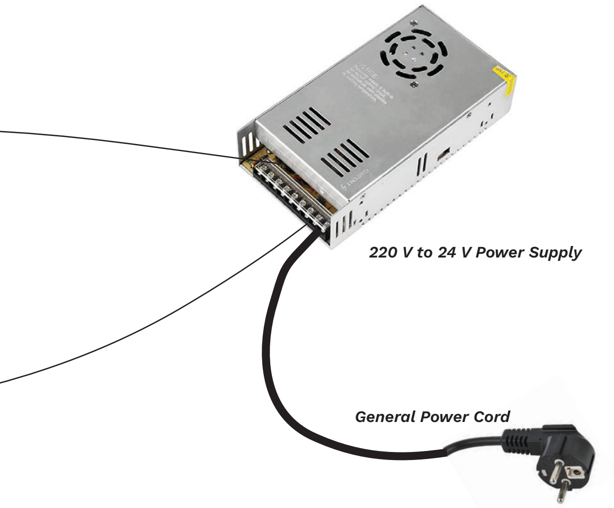
The procedural steps for the Vacuum Thermoforming was to exploit the thermoplastic nature of PLA and check the empirical reactions of heating the specimens and shaping them over a mould under nominal pressure of vacuum. For this the heating setup had to be compatible with the mould and the vacuum bag.

Step 1 Assembling the Heating Mat Circuit

This step was to supply power to the heating mats, as the mats were recieved as standalone devices.
The two heating mats were connected in parallel with a 24 V power suppl sourced from the Lama Lab at TU Delft.

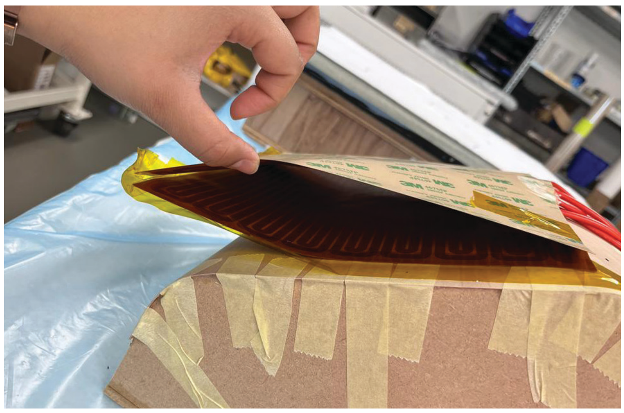
Circuit Essentials
1. 220 V to 24 V, 25 A Power Supply
2. 220 V Power Cord
3. Wago 221 w Way Compact Lever Connectors
4. Wire End Caps

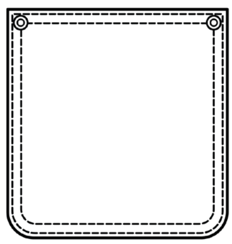




Step 2 Pocketing the Mats, fixing to Mould

This step involved creating a pocket of the mould, and with Kapton Heat Resistant Tape, it was fixed on the Mould, this pocket would hold the specimens.





Step 3 Vacuum Bag Seal with Mould

1 m x 0,6 m vacuum film is cut and sealed with tape, the bag dimensions were such that the mould would be comfortably placed in the seal.

Step 4 Sealing Mould + Specimen in Bag

The specimen is placed in the heating mat pocket and the bag seal is closed. The wires of the Heating mat are also sealed as they connect to the Power Supply outside of the Vacuum Bag Seal as a standard safety procedure, due to the fan in the power supply.

Step 4 Connecting Lines

All lines are checked and connected, Vacuum pump is connected to a Plug seperated from the electrical supply or switch of the heating maps, as the process of Vacuum and Heating are not simulatenous, it was kept separate to have a higher degree of control.

Step 5 Vacuum On

The Vacuum is turned on, till a perfect vacuum is achieved and seals are checked.

Step 6 Heating Circuit Turned On

The mats are switched on while the set up is under vacuum. The mats used in this experiment could reach 120 degrees C in under a minute, upon multiple trials and error it was found that heating the specimen for a minute could maintain the Tg of the PLA = 55-70 C

4.26

Reshaping Cycles

Step 7 Vacuum Turned Off

The Vacuum is turned off, at the 30 seconds mark, and the mat temperature is at 55-70 C. This allows the composite to heat evenly without pressure, as pressure while heating can displace the PLA at the bending region.

Step 8 Heat Turned off

The heating mat is turned off at 1 min mark.

Step 9 Vacuum Turned On

The vacuum pressure is turned on immediately after and a shaping response is seen.

Step 10 Seal Opened & Composite Released.

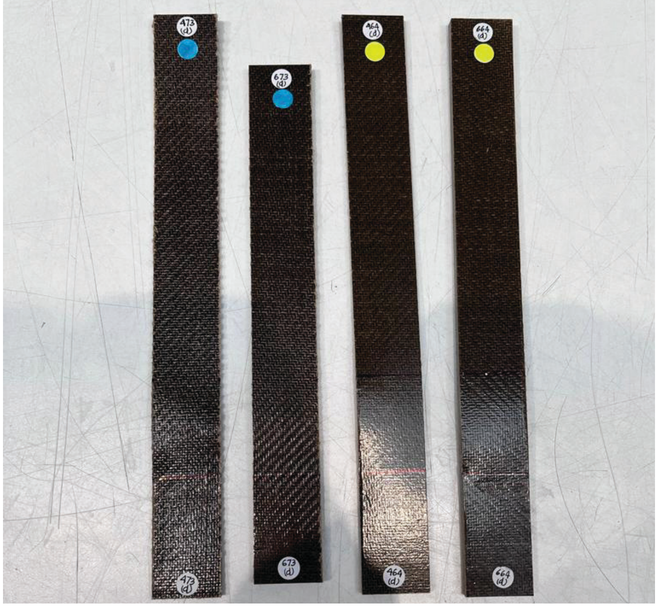
After 2-4 mins (varies across composite types), the vacuum pressure conforms the composite closely with the mould. At room temperature, while the mats are off, the vacuum is turned off, and the seal is opened. Composite shaping is achieved.

Procedure for Reshaping

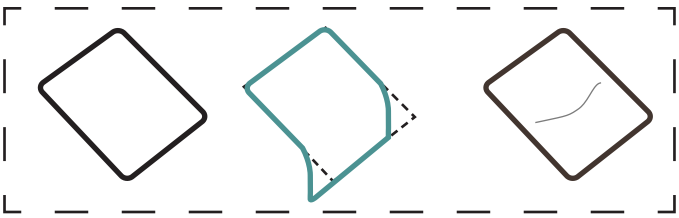
The method for flattening the specimens uses the same above steps, with the mould now turned to it's flat side. This reuses the whole setup without any additional components, and bends the shaped specimens into flat pieces.

BEND_1 TENSILE SPECIMENS

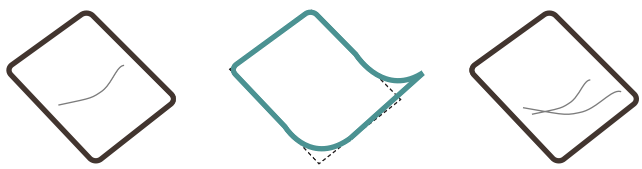
FLATTEN_1 TENSILE SPECIMENS



Shaping Cycle 1



Shaping Cycle 2



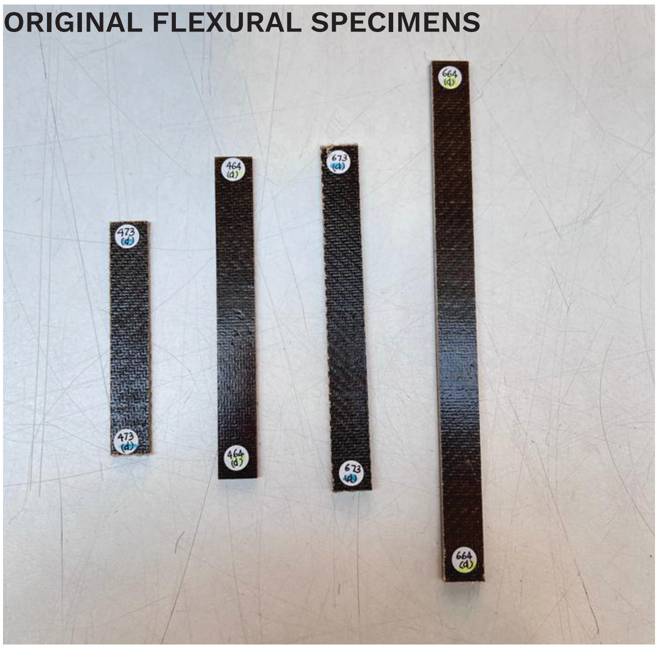
Seal+Heat+Shape > Seal+Heat+Flatten

4.27

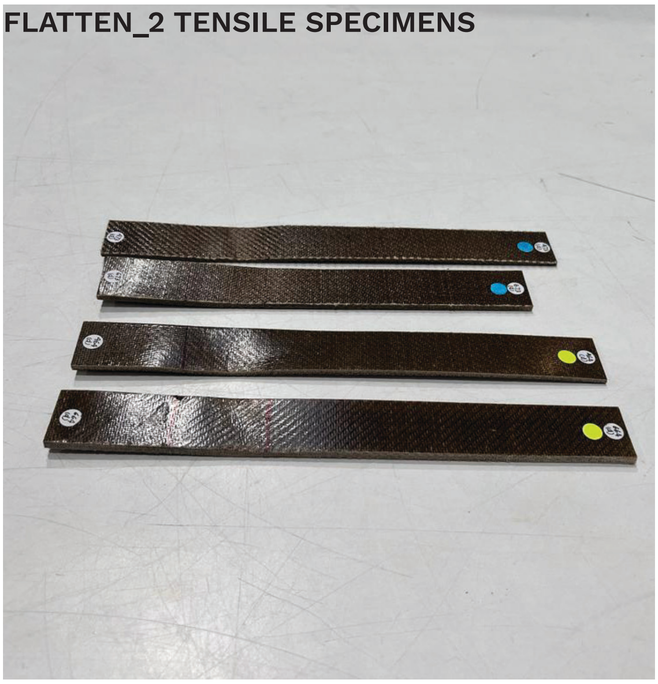
Reshaping Results

BEND_2 TENSILE SPECIMENS

ORIGINAL FLEXURAL SPECIMENS

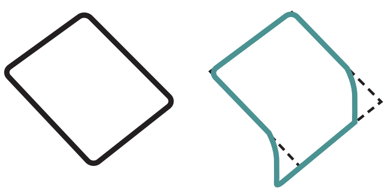


FLATTEN_2 TENSILE SPECIMENS

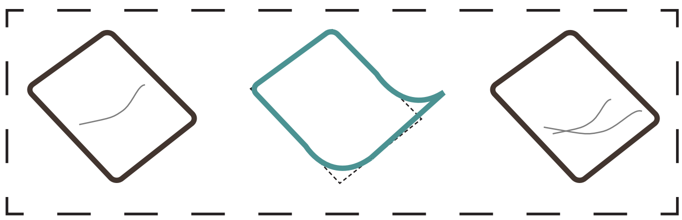


BEND_1 FLEXURAL SPECIMENS

Shaping Cycle 1



Shaping Cycle 2



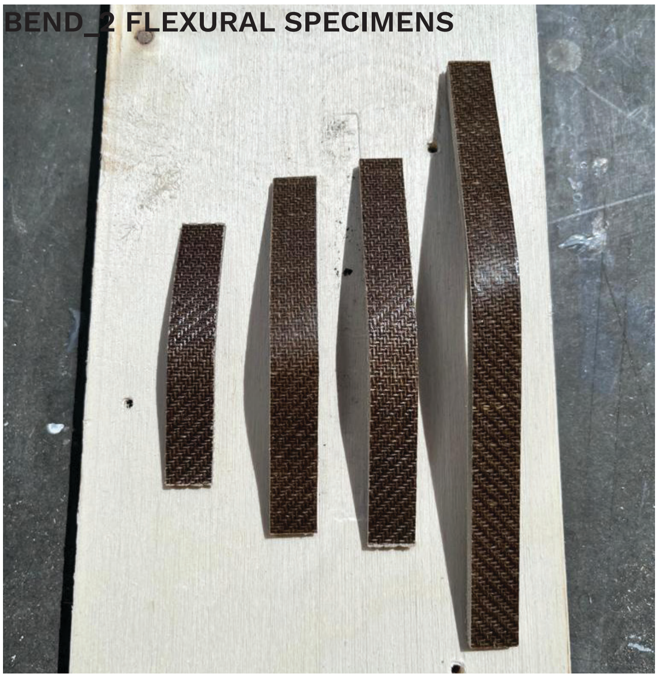
Seal+Heat+Reverse > Seal+Heat+Flatten

4.28

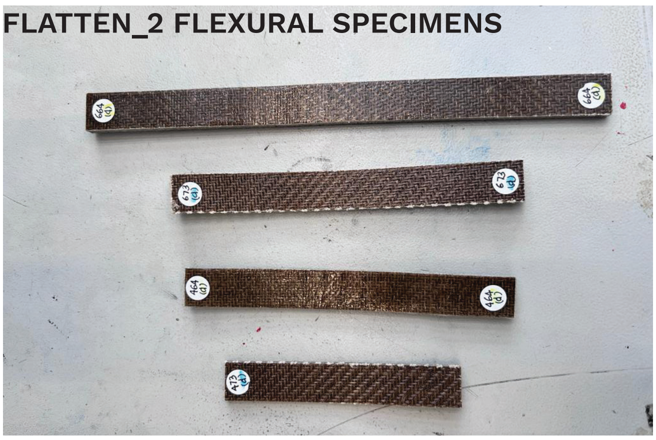
Discussion of Results

FLATTEN_1 FLEXURAL SPECIMENS

BEND_2 FLEXURAL SPECIMENS



FLATTEN_2 FLEXURAL SPECIMENS



Initial Hypothesis
Experiment 3:

Is the proposed reshaping strategy for bio-composites feasible, and if so, what is the level of mould conformity, time and energy expenditures, and characteristics such as texture, appearance for each specimen type?

Yes, the proposed reshaping strategy of vacuum thermoforming using heatpads can reshape the FLAX PLA composite. However, there were some cause-effect links estabilised in the responses.

Cause & Effect Links
Flax Layer & Mould Conformity
It was seen that Composites with lower flax pliers/laminas could bend easier than 6 layer Flax. 4 Layers Flax had higher mould conformity

Mass Ratios & Appearance
There was fading and discolouration in composites with 70:30 ratio upon the second cycle of shaping. Creases and wrinkles were however, lower in appearance in the 60:40 ratio.

Time Required - Mould Conformity
The mass ratios 60:40 took 2-3 mins more time in heat and vacuum than 70:30, to acquire the same radii of curvature. Similarly, time taken by 6 layered flax specimen was higher than the 4 layer flax specimen.

Comparison with Unshaped Specimens
After 2 cycles of shaping, the specimens do show slight degrees of change in appearance, and have residual bends when flattened. This can be repaired with higher times under heat and vacuum but is yet to be documented in bigger profiles.

Mould Conformity = High
Time Required = 1-3 mins to reach Tg
Power Supply = 2A Vacuum, 20 A Mat
Texture = Unchanged for 60:40
Appearance = Fade seen in 70:30

4.29

Experimental Summary

Deriving Results

The Design of Experiments chapter conducted three experiments to optimize bio-composite manufacturing. These experiments explored different techniques, mediums, mass ratios, and fibre lamina ply levels. The findings offer valuable insights for optimizing the production process and understanding the effects of various factors on the resulting bio-composites.

Experiment One

It compared the effectiveness of two production techniques and mediums (Hot Pressing with PLA Film and VARTM with PLA Polyol Resin) regarding consolidation, time, cost, the skill required, and the quality achieved. The observations revealed that Resin Film Infusion (RFI) with PLA Film offered superior results, including better quality and consolidation, shorter processing time, lower cost, and reduced skill requirements compared to VARTM with Polyol Resin.

Experiment Two

Following Resin Film Infusion, this scientific attempt explored the influence of Flax-PLA mass ratios and fibre lamina ply levels on the Resin Film Infusion process and resultant composite traits. The findings showed that higher mass ratios required longer melting times, while the number of flax layers affected the pressure needed for consolidation. Additionally, there was a potential relationship between the mass ratios and achieved texture, with higher PLA content leading to a smoother surface.

Experiment Three

Finally, this research investigated the feasibility of a proposed reshaping strategy for bio-composites using vacuum thermoforming with heat pads. The results confirmed the strategy's feasibility, with variations in mould conformity, appearance, and time requirements based on flax layer count and mass ratios. The 60:40 mass ratio exhibited higher mould conformity and fewer appearance issues than the 70:30 ratio, which experienced fading and wrinkles upon reshaping.

4.30

Test Protocol

Overall, these collective findings enhance the bio-composite manufacturing process, optimise material characteristics, and provide insights into reshaping strategies.

Further investigations are needed to explore the impact of these findings on bigger profiles and to address residual bends observed after reshaping.

Given that the reshaping process may affect the composite's strength and mechanical properties, The reshaped specimens will be tested for tensile strength, flexural strength, and other relevant mechanical properties.

Hypothesis for Testing Post Experiments:

Is there a difference in mechanical properties of the biocomposite before and after reshaping?

ASTM D3039 Tensile Tests

ASTM D7264 Flexural Tests

ASTM D570-22 Water Absorption Tests

Natural Weathering Test

Biodegradability Test

Summary

Chapter 4 of the paper presents three experiments that aim to optimize the manufacturing process of bio-composites and understand the effects of various factors on the resulting bio-composites.

Experiment 1 compared the effectiveness of two production techniques and mediums, and Resin Film Infusion was found to be the most effective technique.

Experiment 2 examined the differences in appearance, texture, time, and energy requirements for maximum consolidation when manufacturing different Flax-PLA mass ratios with varying levels of flax laminae.

Experiment 3 investigated the feasibility and effects of a novel bio-composite reshaping strategy. The case study used in this research offers a practical, real-world perspective on developing the biocomposite, and the testing program involved testing the mechanical properties of the biocomposite before and after reshaping.

It is visually perceived that the reshaping process may affect the few of the 4 composite mechanical properties, and further investigations are needed to explore the impact of these findings on bigger profiles.

The proposed circular strategy of reshaping, reusing, and restoring the biocomposite offers a sustainable and innovative approach to the AEC sector, and the results obtained in this chapter provide a solid foundation for future research in this area.

Overall, this chapter highlights the importance of considering circularity in the design and manufacturing of materials for the AEC sector and provides a practical example of how this can be achieved through the use of bio-composites.

05

testing results research **conclusions**

This chapter will review the experimental results from **testing** to track material behaviour & patterns seen in the Flax+PLA **composite** before and after reshaping.

5.1

Hypothesis for Testing

Data **Recap**

Upon the manufacturing of the Flax-PLA Composites, the next step was to record, validate and cross-verify the mechanical properties of the composites as per macro calculations with the Rule of Mixtures and Technical Data Sheets, and recorded values in reviewed literature of similar working methods i.e. the study conducted by Kazmi & co-workers (2023).

Testing **Purpose**

The purpose of the testing program is to investigate the mechanical properties of the Flax-PLA composite, but also study the empirical differences found in the material if attempted for structural reuse, therefore the reactions of reshaping the material.

1

Hypothesis One

What are the mechanical properties of the composites produced in Experiment 2?

Material Characterization
Examining the mechanical properties gives insights into the **structural** behaviour, **strength** & durability. This is crucial to assess the biocomposite's **suitability** for the **end-use** application of the facade panel.

Testing the original specimens will help determine the baseline mechanical properties.

2

Hypothesis Two

What is the impact on the properties of the specimens before and after reshaping?

Performance Evaluation
Evaluating the properties before and after the shaping cycles allows to assess the impact of the reshaping process on its performance.

Testing the Reshaped Specimens will help determine if upon reshaping, the biocomposite retains its integrity and exhibits desired performance.

5.2

Sample Identification

Label **Codes**

The identification system used for the testing specimens were uniform with the composite coding used in the Experimental Setup previously.

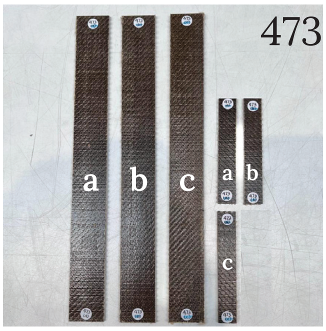
Assignment Logic

Sample ID = $Fn_o\ x_f\ y_p$ — (a/b/c/d)

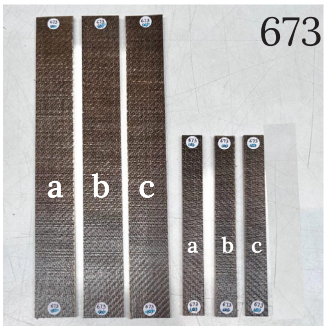
473 4 Layers Flax □70 % Flax : 30 % PLA
673 6 Layers Flax □70 % Flax : 30 % PLA
464 4 Layers Flax □60 % Flax : 40 % PLA
664 6 Layers Flax □60 % Flax : 40 % PLA

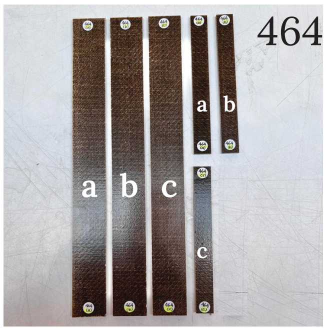
Fn_o = No. of Flax Lamina
x_f = First Number of Flax Mass %
x_p = First Number of PLA Mass %
(a) = Specimen Number

Original Specimens : Tensile & Flexural Test Batch



The specimens from a to c across all composites belong to the Original Specimen testing batch



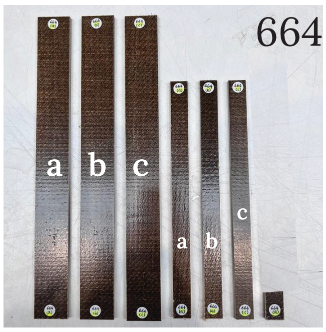


473-a, 473-b, 473-c

673-a, 673-b, 673-c

464-a, 464-b, 464-c

664-a, 664-b, 664-c



5.3
Tensile Test

Tensile Test **Significance**

Tensile strength is crucial in evaluating a biocomposite material's ability to resist breaking or deformation when subjected to pulling forces.
The significance of tensile strength and modulus of elasticity for a biocomposite material, specifically for the context of cladding is as follows:

Integrity & Durability:
Testing the tensile strength ensures its structural integrity by mitigating risk of failure caused by tension forces it may experience in service, due to windloads, temperature variations, potential impacts.

Installation Considerations:
The test results provides insights into the material's resistance to stretching or elongation, which can be crucial for proper installation and avoiding premature damage to the panels.

Code & Compliance Standards:
Tensile strength testing is often a requirement in building codes, standards, and regulations governing facade systems.
By conducting these tests, the biocomposite material can be evaluated against the prescribed performance criteria, ensuring compliance with industry standards and regulatory requirements.

Tensile Test **Protocol - ASTM D3039**

Tensile properties of the biocomposite in this research were evaluated following the guidelines outlined in ASTM D 3039, a recognized standard for testing the tensile properties of Polymer Matrix Composite Materials

Objective

Determination of in-plane tensile properties of the biocomposite is based on the consideration that fibre laminate is balanced and symmetric with respect to test direction.

In-plane tensile strength parameters obtained is used for reviewing the quality of the composite material and expected performance under multiple environmental loading conditions on actual composite cladding panel.

Summary of Test Method:

Code recommended geometry is presented in table below:

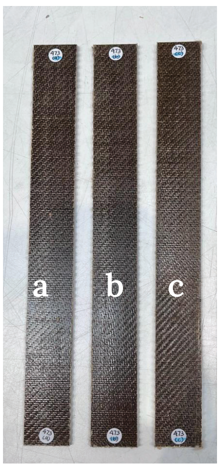
Dimensions Details of Test Specimens

length (mm)	width (mm)	thickness (mm)	remarks
250	25	Per Specimen	Fibre Orientation is considered as balanced & symmetric

Number of Test Specimens

Minimum 3 numbers of test specimens per test conditions were used as valid test results were obtained in 3 numbers of tests itself.

Per ASTM D3039, it is acceptable.

473


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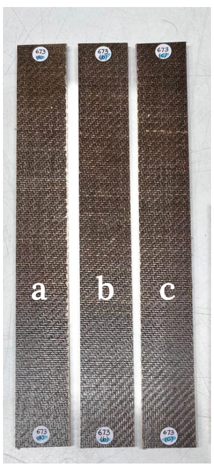
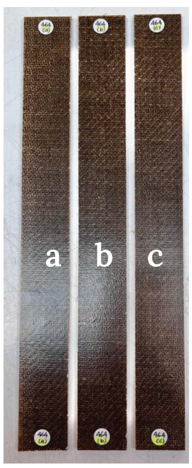
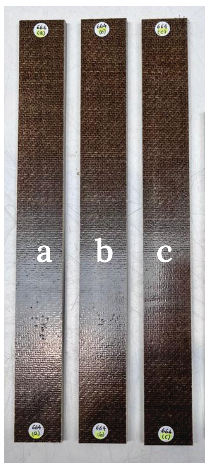


464


664


5.4

Tensile Test Protocol

Test Specimen **Conditioning**

Unconditioned:
All the tests were carried out at unknown moisture content and without any explicit test conditions.

Speed of Testing

Speed of testing was maintained in such a way that strain rate was constant in the gage section and constant speed was maintained as per standard.
The testing stand had a strain rate of 10 mm/min.

Test **Stand**

All tests were done under the supervision of **Professor Fred Veer**, at the 3mE, Mechanical, Maritime and Materials Engineering Department, at the Mechanical Testing Lab.

The testing stand used was a Zwick Z010.

Test **Measurements**

Loadings and corresponding displacements were measured and recorded determination of tensile properties.

Panel Forming Status

Conditioning	Forming	Remarks
Unconditioned	Initial	Without Forming
Unconditioned	Reshaped	Forming in Reverse

Ultimate Tensile Load

Load at failure in addition to various strain level was measured for deriving the ultimate tensile strength.

Ultimate Elongation

Elongation at failure in addition at various load point was measured for determination of strains

Ultimate Tensile Strength

13.1 *Tensile Stress/Tensile Strength*—Calculate the ultimate tensile strength using Eq 5 and report the results to three significant figures. If the tensile modulus is to be calculated, determine the tensile stress at each required data point using Eq 6.

$$F^{tu} = P^{max}/A \quad (5)$$

$$\sigma_i = P_i/A \quad (6)$$

where:

F^{tu} = ultimate tensile strength, MPa [psi];
P^{max} = maximum force before failure, N [lbf];
σ_i = tensile stress at ith data point, MPa [psi];
P_i = force at ith data point, N [lbf]; and
A = average cross-sectional area from 11.2.3, mm^2 [in.^{2}].

Ultimate Tensile Strength

13.2 *Tensile Strain/Ultimate Tensile Strain*—If tensile modulus or ultimate tensile strain is to be calculated, and material response is being determined by an extensometer, determine the tensile strain from the indicated displacement at each required data point using Eq 7 and report the results to three significant figures.

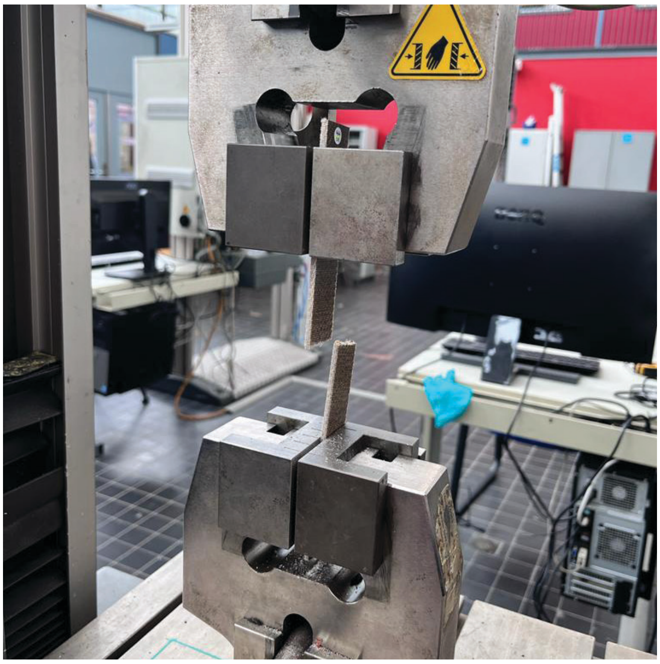
$$\varepsilon_i = \delta_i/L_g \quad (7)$$

where:

ε_i = tensile strain at ith data point, με;
δ_i = extensometer displacement at ith data point, mm [in.]; and
L_g = extensometer gage length, mm [in.].

5.5

Tensile Testing



Chord Modulus of Elasticity

Chord Modulus of Elasticity was calculated considering failure stress point and corresponding stress point at strain 0.2% lower than failure stress point.

Excerpts of ASTM D3039 is presented here for clarity.

$$E^{chord} = \Delta\sigma / \Delta\varepsilon \quad (8)$$

where:

E^{chord} = tensile chord modulus of elasticity, GPa [psi];
$\Delta\sigma$ = difference in applied tensile stress between the two strain points of Table 3, MPa [psi]; and
$\Delta\varepsilon$ = difference between the two strain points of Table 3 (nominally 0.002).

Dimensional Properties

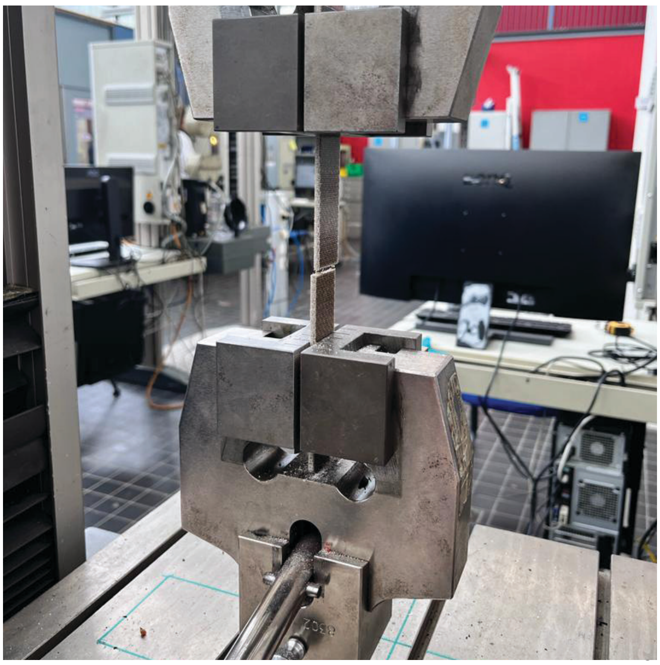
Specimen ID with properties are tabulated below:

Specimen ID	Gauge Length - L_g (mm)	Width - w (mm)	Thickness - h (mm)	Cross-Section Area -A (mm^2)
473-a	94	25	2	50
473-b	94	25	2	50
473-c	94	25	2	50
473-d	94	25	2	50
673 -a	97	25	3	75
673-b	97	25	3	75
673 -c	97	25	3	75
673 -d	97	25	3	75
464 -a	97	25	2.8	70
464 -b	97	25	2.8	70
464 -c	97	25	2.8	70
464 -d	97	25	2.8	70
664 -a	103	25	4.5	112.5
664 -b	103	25	4.5	112.5
664 -c	103	25	4.5	112.5
664 -d	103	25	4.5	112.5

Reshaped Specimens

In the context of reshaped specimens (-d), critical areas within the **bending regions were designated** for careful analysis to ascertain whether tensile failure occurred within these regions.

Upon investigation, it was established that the tensile failure was indeed localised within the bending regions for the reshaped specimens. Conversely, all the unshaped specimens demonstrated **failure centrally.**



5.6

Tensile Test Results

Tensile **Properties**

473-d, 673-d, 464-d and 664 -d specimens were reshaped and tested
Other Test specimens are tested before reshaping.

All the tensile properties of all the specimens are tabulated as listed below

Specimen ID	Ultimate Tensile Load- P^{max} (N)	Ultimate Elongation δ (mm)	Ultimate Tensile Strain – ε	Ultimate Tensile Strength- F^{tu} (MPa)	Ultimate Tensile Strain – ε (%)	Chord Modulus of Elasticity - E^{chord} (GPa)
473-a	5849	5.429	0.058	116.980	5.827	1.268
473-b	5777	5.802	0.062	115.540	6.173	1.287
473-c	5663	5.488	0.058	113.260	5.842	1.171
473-d	4343	5.725	0.061	86.860	6.131	0.940
673 -a	9282	6.670	0.069	123.760	6.876	1.390
673-b	9451	6.376	0.066	126.013	6.574	1.251
673 -c	9437	6.235	0.064	125.827	6.427	1.124
673 -d	7398	5.623	0.058	98.640	5.797	1.179
464 -a	6723	5.821	0.060	96.043	6.001	1.151
464 -b	7185	6.031	0.062	102.643	6.217	1.288
464 -c	7107	5.753	0.059	101.529	5.931	1.146
464 -d	5968	5.426	0.056	85.250	5.593	1.254
664 -a	10799	6.121	0.059	95.991	5.943	1.164
664 -b	11169	6.273	0.061	99.280	6.250	1.096
664 -c	11200	6.273	0.061	99.556	6.090	1.133
664 -d	8918	6.581	0.064	79.271	6.389	1.069

5.7

Summary of Tensile Results

Summary of **Tensile Properties * (Category Wise)**

The average properties of each Composite material category and the corresponding properties of reshaped specimens are tabulated and analysed.

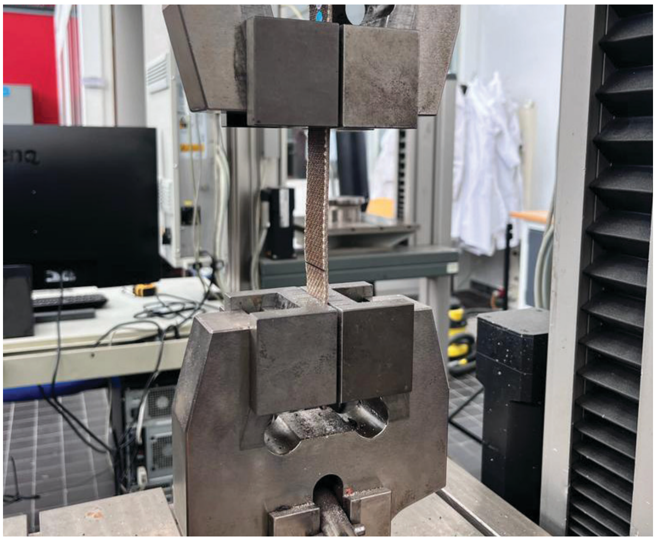
Table - C 473 - Ultimate Tensile Properties Before & After Reshaping

Description	Value	Unit
F^{tu} Ultimate Tensile Strength	115.260	MPa
E^{chord}-Chord Modulus of Elasticity	1.242	GPa
ε - Ultimate Tensile Strain	5.947	%
F^{tu} Ultimate Tensile Strength - Reshaped	86.86	MPa
E^{chord}-Chord Modulus of Elasticity - Reshaped	0.940	GPa
ε - Ultimate Tensile Strain - Reshaped	6.131	%

Table - C 673 - Ultimate Tensile Properties Before & After Reshaping

Description	Value	Unit
F^{tu} Ultimate Tensile Strength	125.200	MPa
E^{chord}-Chord Modulus of Elasticity	1.255	GPa
ε - Ultimate Tensile Strain	6.626	%
F^{tu} Ultimate Tensile Strength - Reshaped	98.64	MPa
E^{chord}-Chord Modulus of Elasticity - Reshaped	1.179	GPa
ε - Ultimate Tensile Strain - Reshaped	5.797	%

c-473



c-673

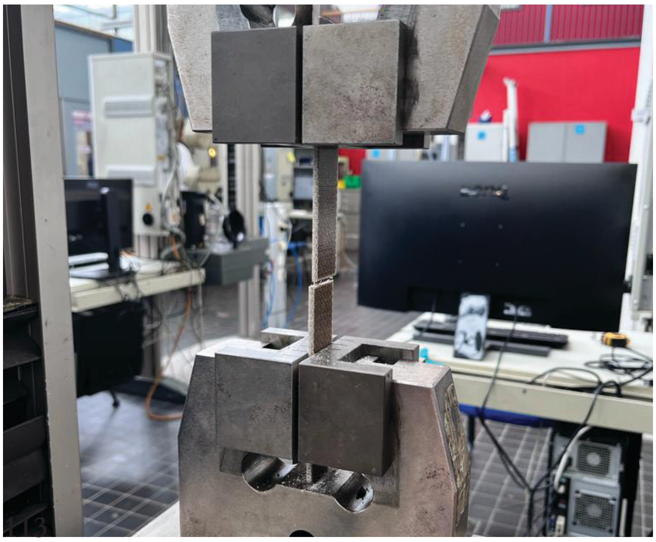
Table - C 464 - Ultimate Tensile Properties Before & After Reshaping

Description	Value	Unit
F^{tu} Ultimate Tensile Strength	100.071	MPa
E^{chord}-Chord Modulus of Elasticity	1.195	GPa
ε - Ultimate Tensile Strain	6.050	%
F^{tu} Ultimate Tensile Strength - Reshaped	85.250	MPa
E^{chord}-Chord Modulus of Elasticity - Reshaped	1.254	GPa
ε - Ultimate Tensile Strain - Reshaped	5.593	%

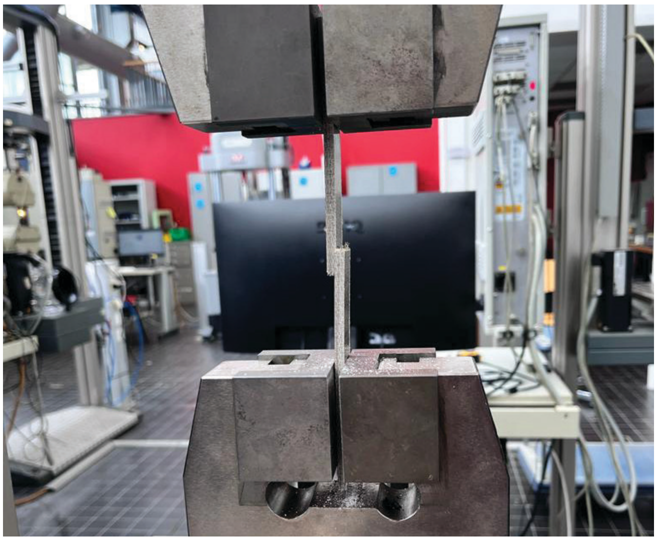
Table - C 664 - Ultimate Tensile Properties Before & After Reshaping

Description	Value	Unit
F^{tu} Ultimate Tensile Strength	98.276	MPa
E^{chord}-Chord Modulus of Elasticity	1.131	GPa
ε - Ultimate Tensile Strain	6.095	%
F^{tu} Ultimate Tensile Strength - Reshaped	79.271	MPa
E^{chord}-Chord Modulus of Elasticity - Reshaped	1.069	GPa
ε - Ultimate Tensile Strain - Reshaped	6.389	%

c-464



c-664

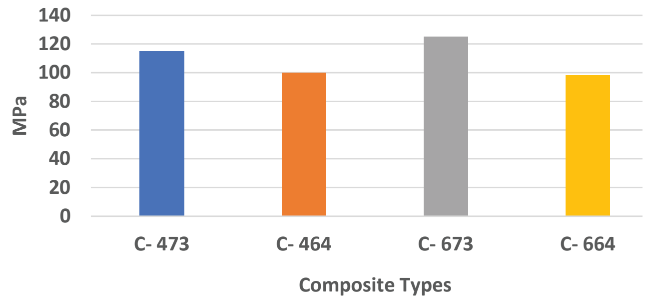


5.8

Comparison of Tensile Properties

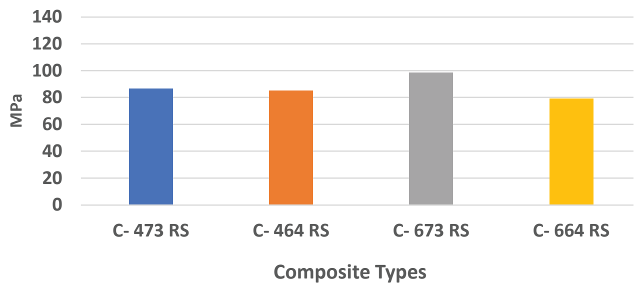
Ultimate **Tensile Strength before Reshaping**

Properties before reshaping are compared below.

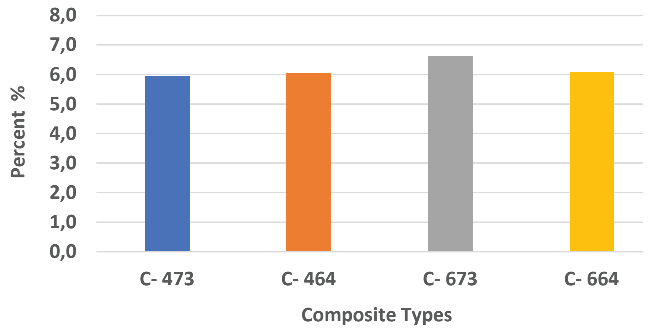


Ultimate **Tensile Strength after Reshaping**

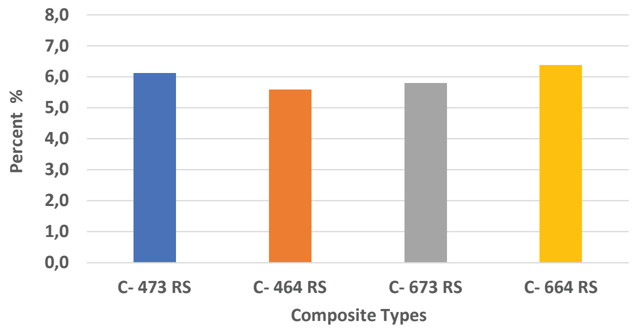
Properties after reshaping are compared below.



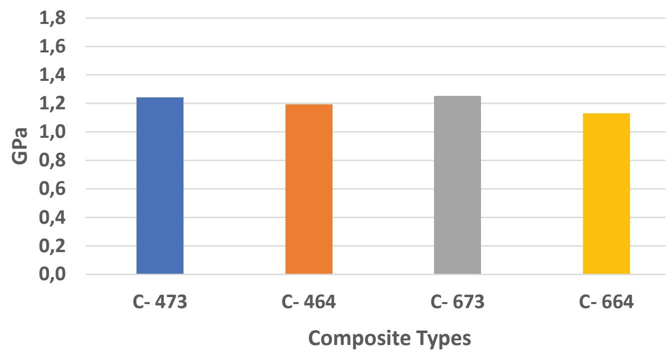
Ultimate **Tensile Strain before Reshaping**



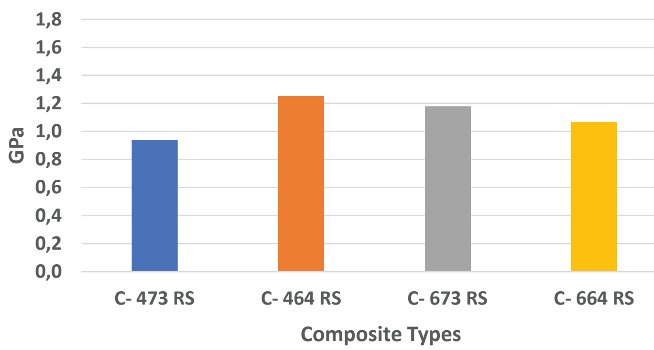
Ultimate **Tensile Strain after Reshaping**



Chord Modulus of Elasticity before Reshaping



Chord Modulus of Elasticity after Reshaping



Original Specimen
Failure Type

LGM

Reshaped Specimen
Failure Type

XGM

First Character

Failure Type	Code
Angled	A
edge Delamination	D
Grip/tab	G
Lateral	L
Multi-mode	M(xyz)
long. Splitting	S
eXplosive	X
Other	O

Second Character

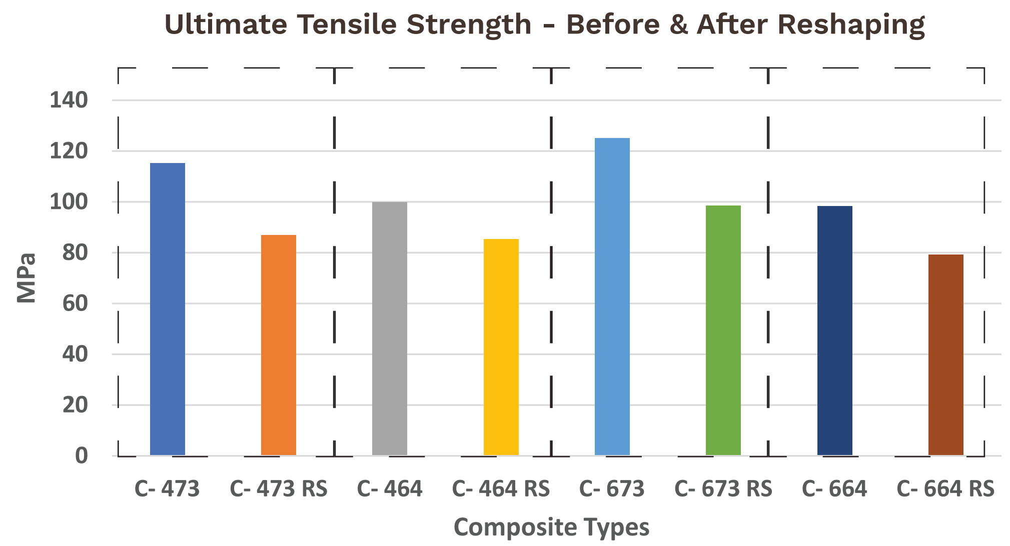
Failure Area	Code
Inside grip/tab	I
At grip/tab	A
<1W from grip/tab	W
Gage	G
Multiple areas	M
Various	V
Unknown	U

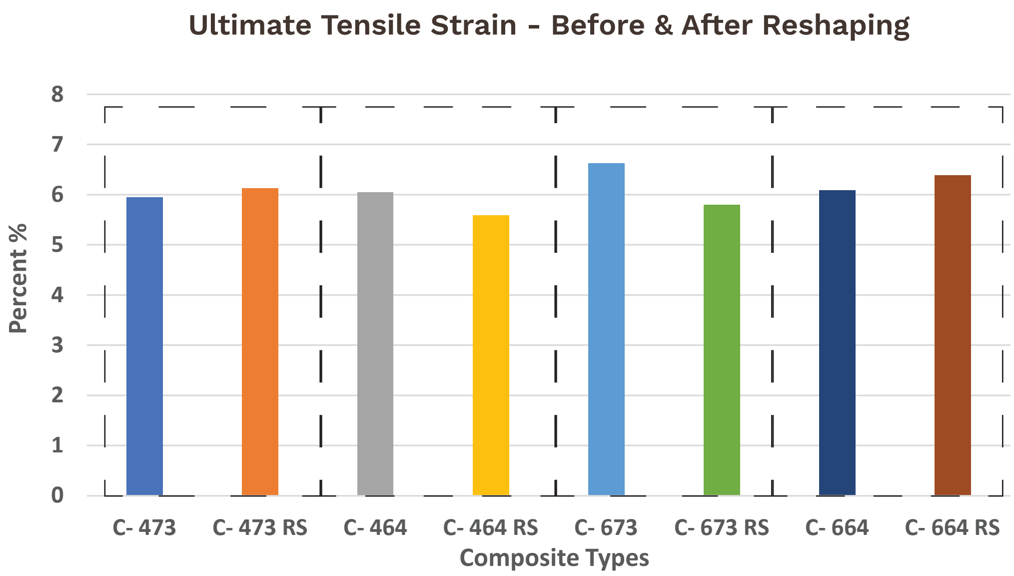
Third Character

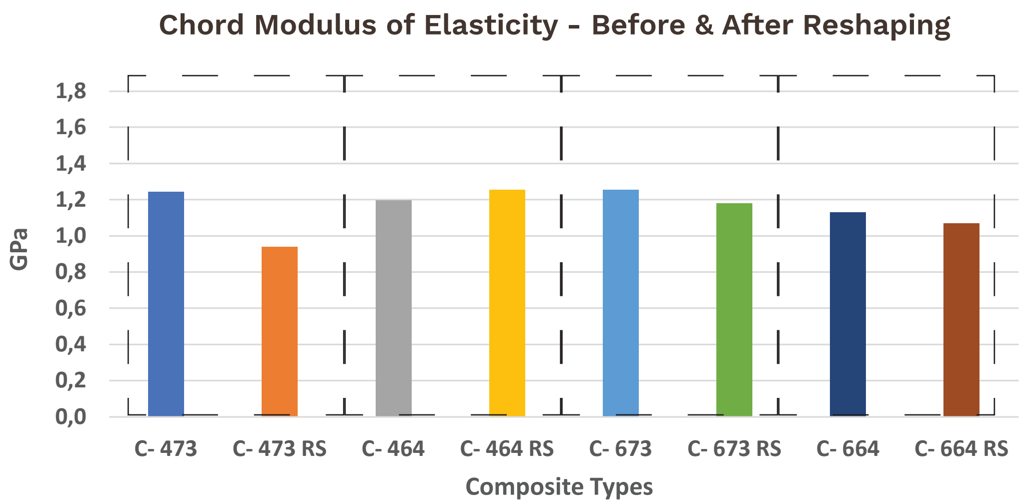
Failure Location	Code
Bottom	B
Top	T
Left	L
Right	R
Middle	M
Various	V
Unknown	U

5.9

Summary of Comparisons





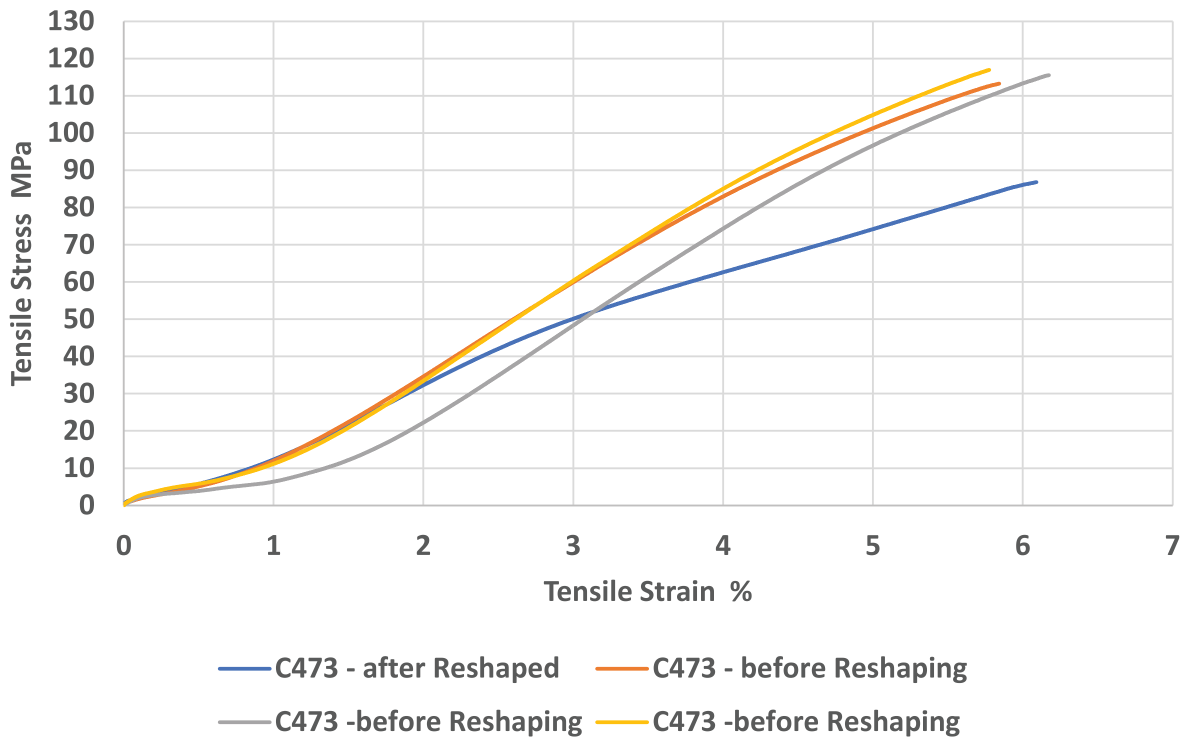


5 . 10

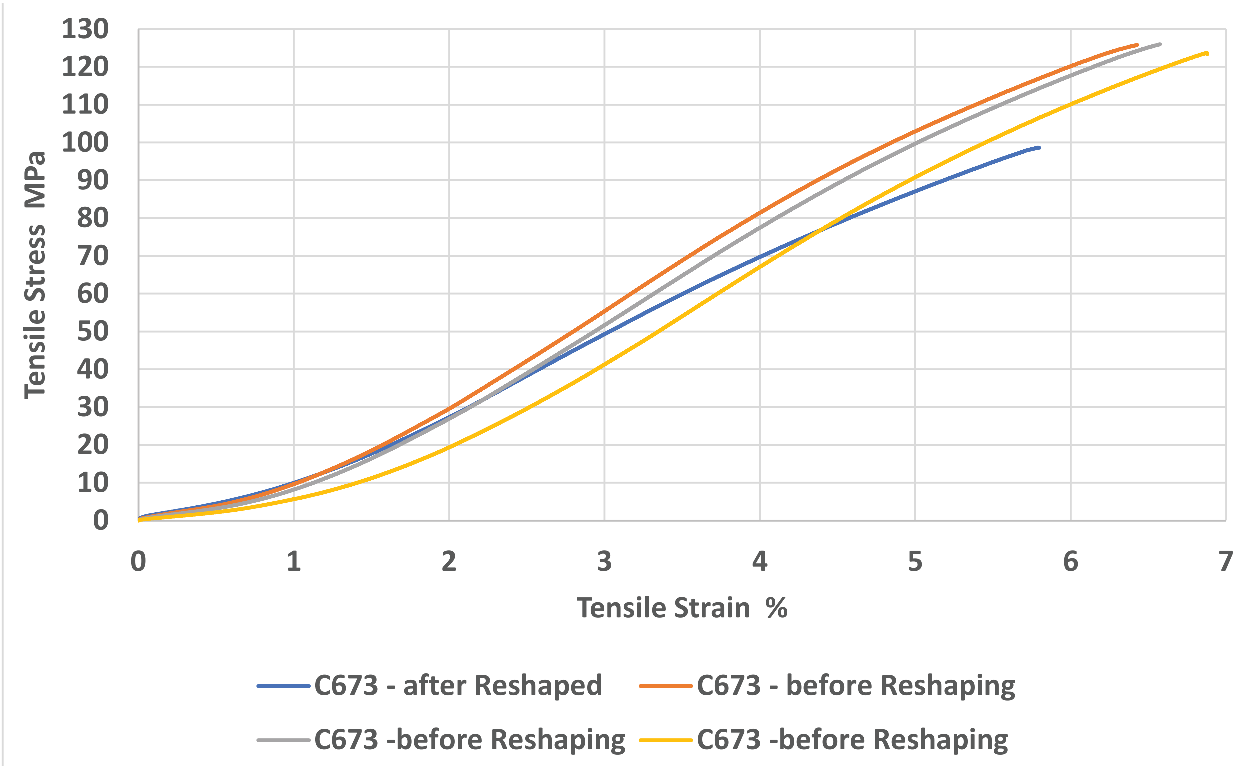
Stress-Strain Curves

Comparison of Strength Properties with Stress-Strain Curves

C473 Tensile Stress - Strain Curve (Before & After Reshaping)

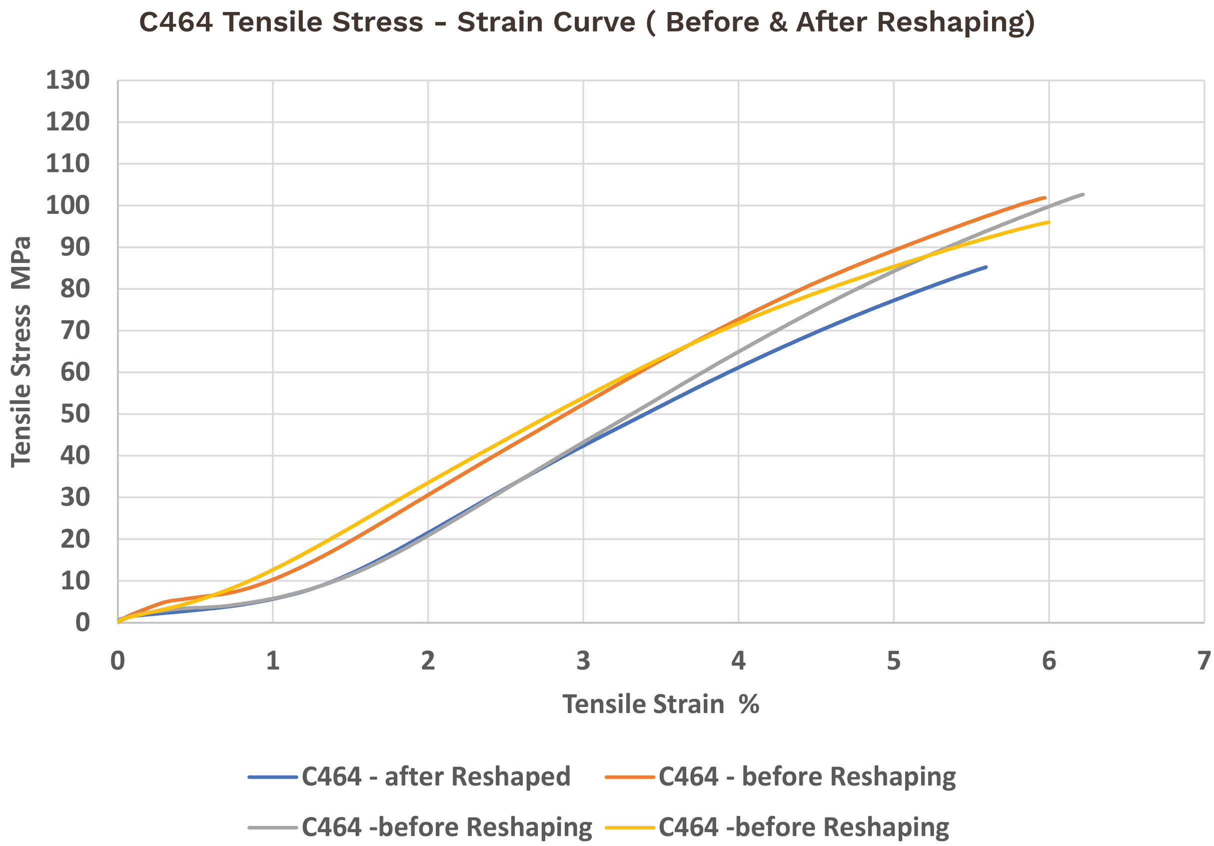


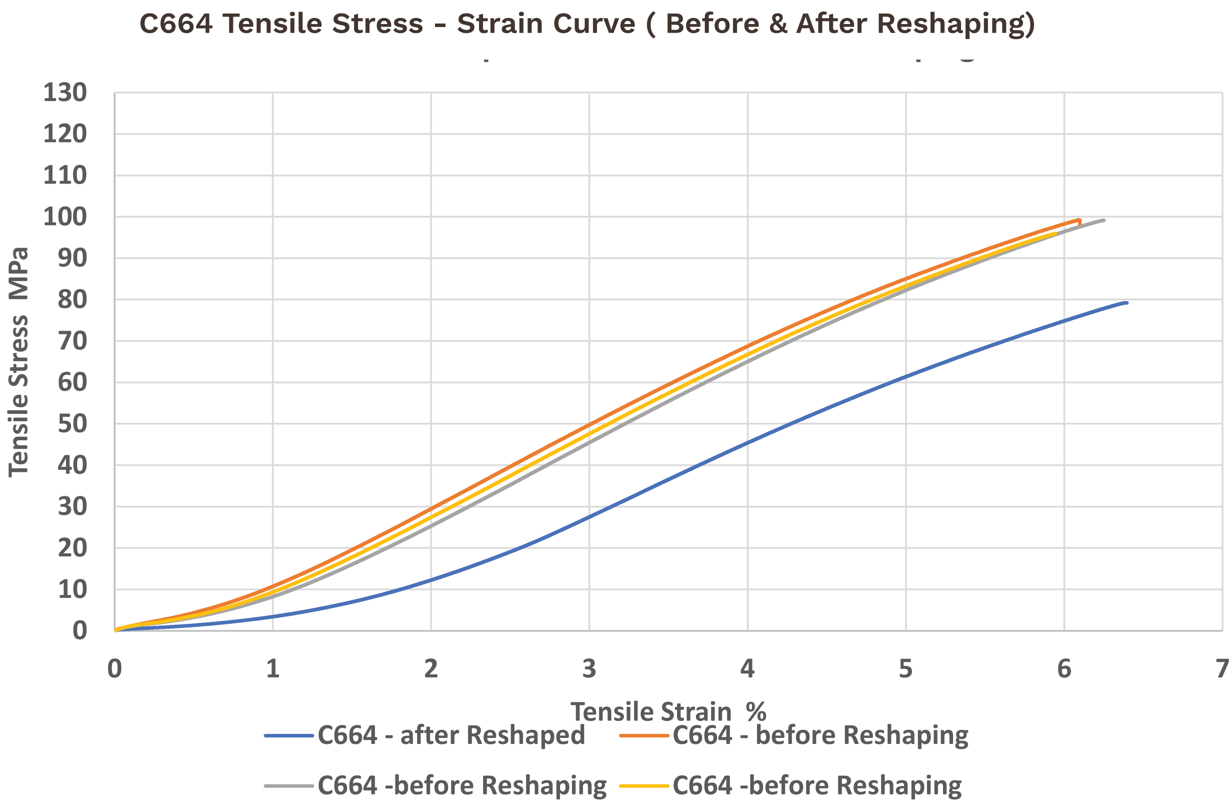
C673 Tensile Stress - Strain Curve (Before & After Reshaping)



5. 10

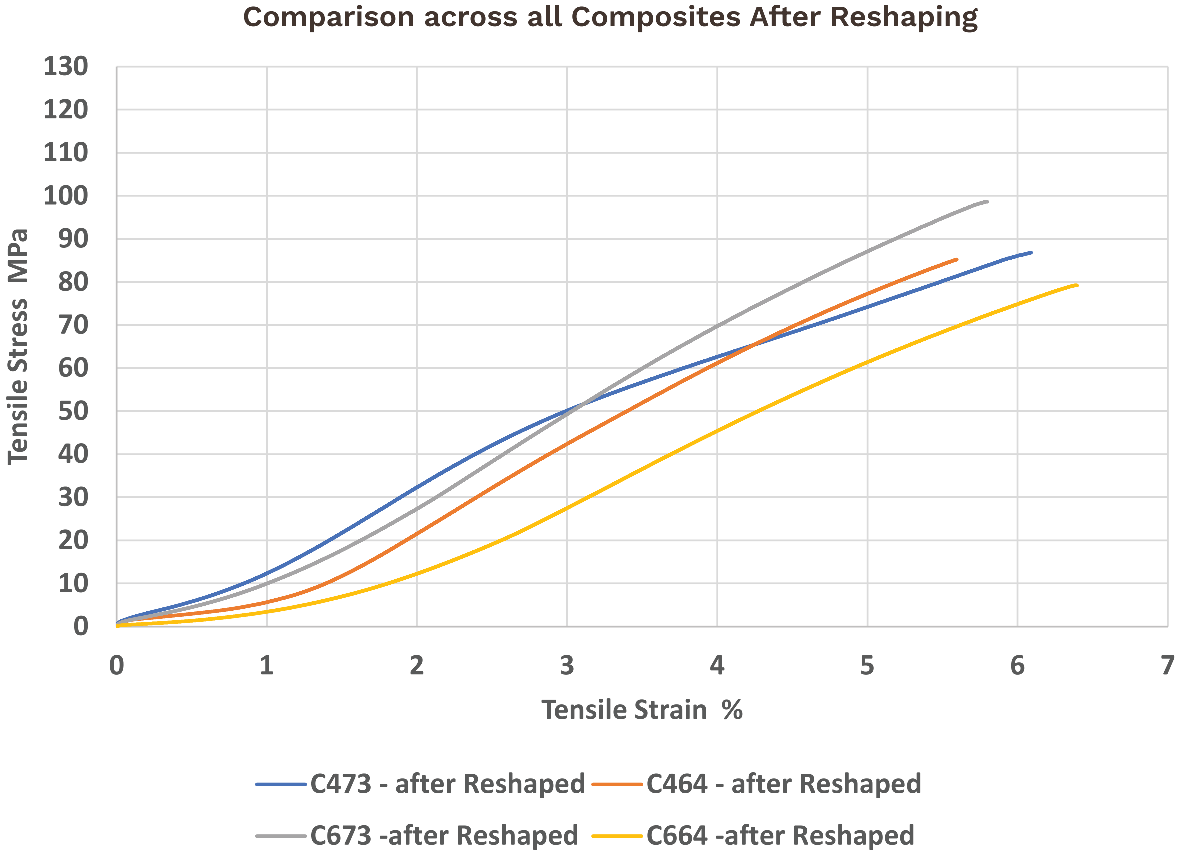
Stress-Strain Curves





5.11

Discussion on Effects of Reshaping



Effects of Reshaping on Tensile Properties

Based on all detailed analyses of test results presented in tables and graphs, the following observations on the impact on Tensile properties are observed.

Impact of Reshaping on Ultimate Tensile Strength

1. The Ultimate Tensile Strength of composites is reduced due to reshaping. Value is decreased from 15% to 25% depending on Flax and PLA ratio.

2. Reduction is less when the PLA ratio increases, or Flax content in the composite is reduced.

3. Ultimate strength reduction was found less in C464 (15%) than in C473 (25%).

With the increase in thickness of composites and so increasing the Flax and PLA quantities, Ultimate Strength increased as expected in the case of 70:30 - Flax: PLA mix, but the same increase was not found in the case of 60:40 - Flax: PLA mix.

Ultimate strength was found in the same range for 4 and 6 layers of Flax for the 60:40 and 70:30 Flax PLA ratio.

However, the decrease in strength was more pronounced in 6-Layered Flax Composites than in 4-layered Flax composites, as a reduction in Ultimate Strength was 15% in C464, while it was 19% in C664.

This is one of the attributes which C464 can be preferred for making the prototype panel.

5.12

Discussion of Results

Impact of Reshaping on Ultimate Tensile Strain

1. Though the Ultimate Tensile Strength of composites is reduced due to reshaping, no set pattern was observed in the impact of the value of ultimate strain near failure. However, in most cases, the reduced stress level was observed for the same strain range for the reshaped specimen.

2. The only exception, in this case, was Specimen C464. In this case, a slightly higher stress level was observed for the same strain range for the reshaped specimen value. However, this may be attributed to reasons value decreased from 15% to 25% depending on Flax and PLA ratio.

3. The ultimate strain value increased in the reshaped specimen when the thickness of the composites was increased while keeping the Flax-PLA ratio the same. In this case Flax: PLA ratio was 60:40.

4. Interestingly Ultimate strain value decreased in the reshaped specimens when the thickness of the composites was increased while keeping the Flax-PLA ratio the same. In this case Flax: PLA ratio was 70:30.

Impact of Reshaping on Ultimate Tensile Strain

1. The Chord Modulus of Elasticity got reduced due to reshaping in all situations except in one case, which appears to be an aberration. Reduction varies from 5% to 24%. For thicker composites, the chord modulus of elasticity reduction is less, around 5 to 6%.

2. There is a definite reduction in stress level for the same unit strain at the failure region.

3. Modulus value increased for reshaped material compared to reshaping when the Flax PLA ratio is decreased and Flax layers are increased. However, the Modulus value decreased for reshaped material compared to before reshaping when the Flax PLA ratio decreased, and the Flax layers increased.

4. Changes in Modulus value are more pronounced after reshaping than before.

5.13

Limitations

Limitations & Variations of Test Results

1. Test results of Tensile properties depend on the manufacturing process of fibres and composites, especially fibre alignments.

2. Gripping at the end of the test specimens and alignment during testing are other factors that affect test results.

3. The ultimate strain value increased in the reshaped specimen when the thickness of the composites was increased while keeping the Flax-PLA ratio the same. In this case Flax: PLA ratio was 60:40.

4. The number of specimens of reshaped material was limited, so more specimens were preferred. However, results are very consistent and in the expected range.

Scientific Summary

This analysis discusses the impact of reshaping on the tensile properties of composite materials made from Flax and polylactic acid (PLA). The critical tensile properties evaluated are Ultimate Tensile Strength, Ultimate Tensile Strain, and Chord Modulus of Elasticity.

The ratio of Flax to PLA and the number of layers in the composites vary in the tests. The Ultimate Tensile Strength, the maximum stress a material can withstand while being stretched or pulled before breaking, decreases due to reshaping.
This decrease ranges between 15% and 25% depending on the Flax to PLA ratio. The strength reduction is less when the proportion of PLA in the composite increases.

In terms of the Ultimate Tensile Strain, which measures the deformation or change in length of the material at the fracture point, there is no consistent pattern after reshaping. However, lower stress levels are typically observed for the same strain range for reshaped specimens. Interestingly, the ultimate strain value varies when the composite thickness is increased with constant Flax: PLA ratio - increasing in a 60:40 ratio but decreasing in a 70:30 ratio.

Lastly, the Chord Modulus of Elasticity, a measure of a material's stiffness, generally decreases with reshaping, with reductions varying between 5% to 24%. However, the modulus value increases when the Flax: PLA ratio decreases while increasing the flax layers.

5.14

Flexural Test

Flexural Test **Significance**

Flexural strength testing, often referred to as a bending test, is a critical evaluation method for materials intended for use in facade cladding panels. It serves several significant purposes:

Integrity & Durability:
This test provides insight into how the material behaves under bending or flexural stress. In a facade cladding application, this data can predict how panels will respond to various stressors such as wind loads, thermal expansion, or the weight of the panels themselves.

Installation Considerations:
The results of the flexural test can offer insights into the material's resistance to bending or deformation, which are critical for accurate installation and preventing premature damage to the panels.

Code & Compliance Standards:
Ensuring that a material has an appropriate flexural strength for its intended application can prevent structural failure, providing a safer end product. It also helps in compliance with the building codes and regulations that often specify minimum strength values.

Flexural Test **Protocol - ASTM D7264**

Flexural properties of the biocomposite in this research were evaluated following the guidelines outlined in ASTM D7264, a recognized standard for testing the flexural properties of Polymer Matrix Composite Materials

Objective

The test determines the biocomposite's flexural strength, flexural modulus and load-deflection behaviour. For this test, **flexural strength** is defined as maximum stress at the outer surface of the test specimen corresponding to the peak applied force prior to flexure failure.

In contrast, **flexural modulus** is defined as the stress range ratio to the test specimen's corresponding strain range.

Flexural strength parameters obtained are used to review the composite material's quality for use as a cladding material for the proposed case study and expected performance under multiple environmental loading conditions.

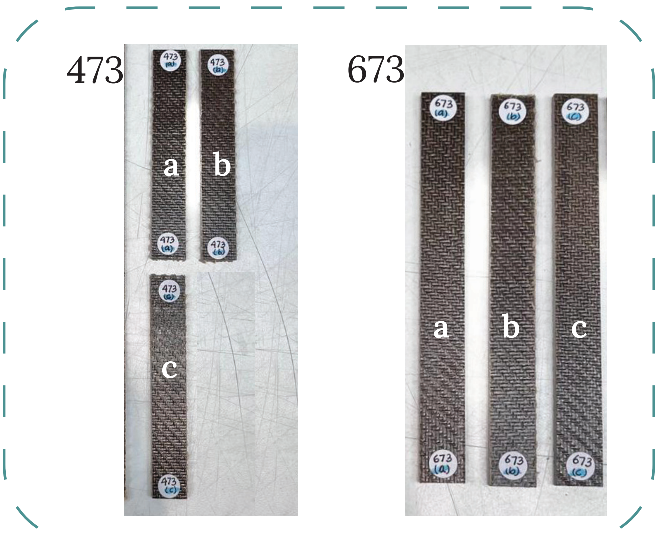
span	width	thickness	remarks
As per ASTM D7264	13	As per Specimen	Fibre Orientation is considered as balanced & symmetric

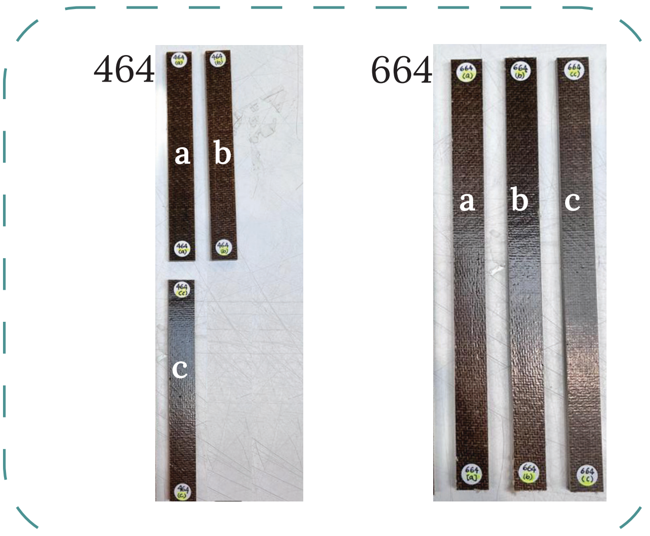
Thickness after consolidation of bio-composites are indicated.

Number of Test Specimens

Minimum 3 numbers of test specimens per test conditions were used as valid test results were obtained in 3 numbers of tests itself.

Per ASTM D7264 it is acceptable.





5.15

Flexural Test Protocol

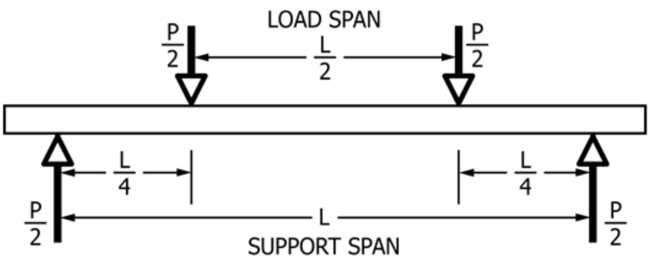
Summary **Test Method**

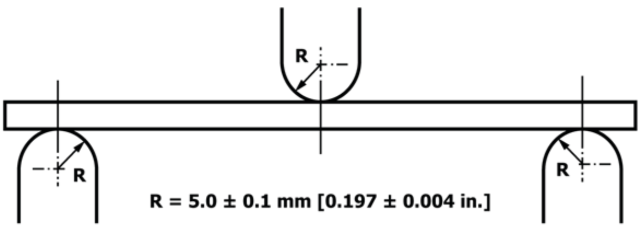
Configuration:
3 Point loading configuration is selected as it simulates the loadings on the bio-composite panel.

Span to Thickness Ratio

Total length of the specimen is kept 20% more the span. Standard specimen width is 13 mm and same is used in this case. Code recommended geometry was followed.

3 Point Test Loading Diagrams from ASTM D7264





Three-Point Loading Configuration with Fixed Supports and Loading Nose

Test Specimen **Conditioning**

Unconditioned:
All the tests were carried out at unknown moisture content and without any explicit test conditions.

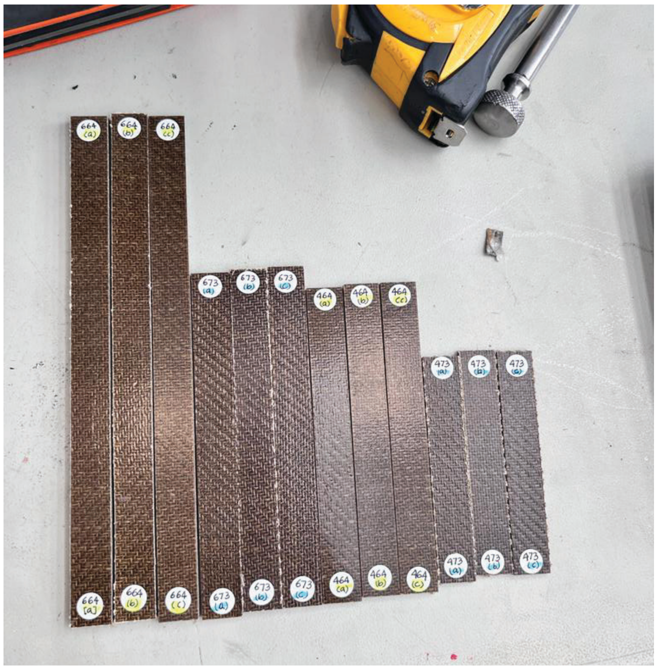
Speed of Testing

Speed of testing was maintained in such a way that strain rate was constant in the gage section and constant speed was maintained as per standard.
The testing stand had a strain rate of 10 mm/min.

Test **Stand**

All tests were done under the supervision of **Professor Fred Veer**, at the 3mE, Mechanical, Maritime and Materials Engineering Department, at the Mechanical Testing Lab.

The testing stand used was a Zwick Z010.



Test **Measurements**

Loadings and corresponding displacements were measured and recorded determination of flexural properties.

Panel Forming Status

Conditioning	Forming	Remarks
Unconditioned	Initial	Without Forming
Unconditioned	Reshaped	Forming in Reverse

Maximum Stress

13.2 *Maximum Flexural Stress, Procedure B*—When a beam of homogeneous, elastic material is tested in flexure as a beam simply supported at two outer points and loaded at two central points separated by a distance equal to ½ the support span and at equal distance from the adjacent support point, the maximum stress at the outer surface occurs between the two central loading points that define the load span (Fig. 2). The stress shall be calculated for any point on the load-deflection curve by the following equation (Note 7):

$$\sigma = \frac{3PL}{4bh^2} \quad (2)$$

where:

σ = stress at the outer surface in the load span region, MPa [psi],
P = applied force, N [lbf],
L = support span, mm [in.],
b = width of beam, mm [in.], and

Maximum Strain

13.5 *Maximum Strain, Procedure A*—The maximum strain at the outer surface also occurs at mid-span, and it shall be calculated as follows:

$$\varepsilon = \frac{6\delta h}{L^2} \quad (3)$$

where:

ε = maximum strain at the outer surface, mm/mm [in./in.],
δ = mid-span deflection, mm [in.],
L = support span, mm [in.], and
h = thickness of beam, mm [in.].

Flexural Chord Modulus of Elasticity

13.7 *Flexural Modulus of Elasticity:*

13.7.1 *Flexural Chord Modulus of Elasticity*—The flexural chord modulus of elasticity is the ratio of stress range and corresponding strain range. For calculation of flexural chord modulus, the recommended strain range is 0.002 with a start point of 0.001 and an end point 0.003. If the data is not available at the exact strain range end points (as often occurs with digital data), use the closest available data point. Calculate the flexural chord modulus of elasticity from the stress-strain data using Eq 5 (for multidirectional or highly orthotropic composites, see Note 8).

$$E_f^{chord} = \frac{\Delta\sigma}{\Delta\varepsilon} \quad (5)$$

where:

E_f^{chord} = flexural chord modulus of elasticity, MPa [psi],
$\Delta\sigma$ = difference in flexural stress between the two selected strain points, MPa [psi], and
$\Delta\varepsilon$ = difference between the two selected strain points (nominally 0.002).

Dimensional Properties

Specimen ID with properties are tabulated below:

Specimen ID	Support Span - L (mm)	Width - b (mm)	Thickness -h (mm)	Cross-Section Area -A (mm²)
473-a	40	13	2	26
473-b	40	13	2	26
473-c	40	13	2	26
473-d	40	13	2	26
673 -a	80	13	3	39
673-b	80	13	3	39
673 -c	80	13	3	39
673 -d	80	13	3	39
464 -a	80	13	2.8	36.4
464 -b	80	13	2.8	36.4
464 -c	80	13	2.8	36.4
464 -d	80	13	2.8	36.4
664 -a	130	13	4.5	58.5
664 -b	130	13	4.5	58.5
664 -c	130	13	4.5	58.5
664 -d	130	13	4.5	58.5

5 . 16

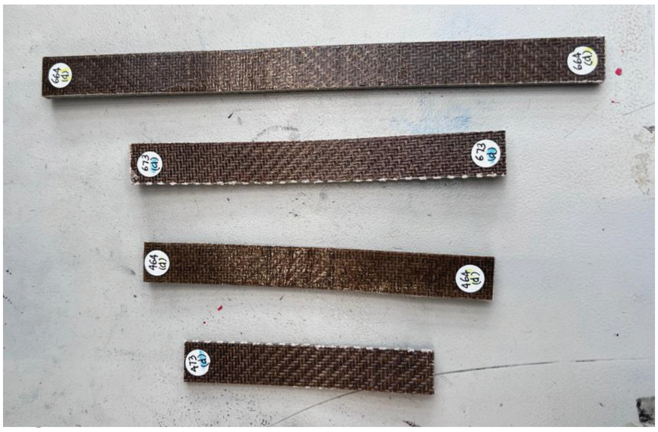
Flexural Testing

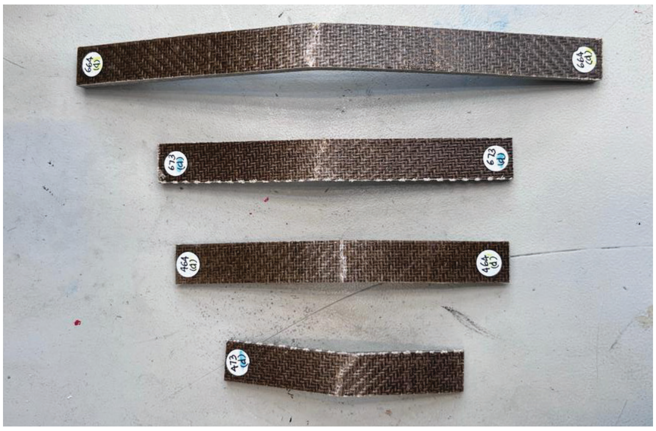
Flexural **Properties**

473-d, 673-d, 464-d and 664 -d specimens were reshaped and tested
Other Test specimens are tested before reshaping.

All the Flexural properties of all the specimens are tabulated as listed below

Specimen ID	Flexural Strain at Max Stress - ε	Max Flexural Stress-σ (MPa)	Max Flexural Strain - ε (%)	Chord Modulus of Elasticity - E_f^{chord} (GPa)
473-a	0.022	195.069	2.215	3.566
473-b	0.023	223.131	2.281	3.009
473-c	0.024	214.855	2.402	3.530
473-d	0.034	170.166	3.447	1.530
673 -a	0.018	190.308	1.837	4.077
673-b	0.021	200.484	2.074	4.702
673 -c	0.017	189.644	1.734	4.376
673 -d	0.029	162.532	2.927	0.855
464 -a	0.025	171.619	2.529	1.823
464 -b	0.026	169.332	2.618	1.724
464 -c	0.025	154.131	2.470	1.759
464 -d	0.028	127.976	2.843	1.200
664 -a	0.028	128.380	2.791	0.846
664 -b	0.029	123.429	2.872	0.658
664 -c	0.027	132.684	2.734	1.193
664 -d	0.034	106.858	3.426	0.267





5.17

Summary of Flexural Results

Summary of **Flexural Properties * (Category Wise)**

The average properties of each Composite material category and the corresponding properties of reshaped specimens are tabulated and analysed.

Table - C 473 - Flexural Properties Before & After Reshaping

Description	Value	Unit
σ Max Flexural Strength	211.019	MPa
E_f^{chord}-Chord Modulus of Elasticity	3.368	GPa
ε - Max Flexural Strain	2.299	%
σ Max Flexural Strength - Reshaped	170.166	MPa
E_f^{chord}-Chord Modulus of Elasticity - Reshaped	1.530	GPa
ε - Max Flexural Strain - Reshaped	3.447	%

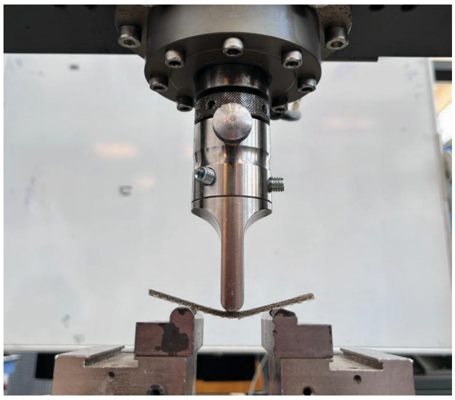


Table - C 673 - Flexural Properties Before & After Reshaping

Description	Value	Unit
σ Max Flexural Strength	193.478	MPa
E_f^{chord}-Chord Modulus of Elasticity	4.385	GPa
ε - Max Flexural Strain	1.881	%
σ Max Flexural Strength - Reshaped	162.532	MPa
E^{chord}-Chord Modulus of Elasticity - Reshaped	0.855	GPa
ε - Max Flexural Strain - Reshaped	2.927	%

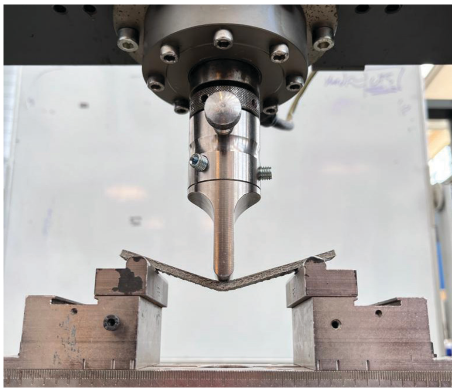


Table - C 464 - Flexural Properties Before & After Reshaping

Description	Value	Unit
σ Max Flexural Strength	165.027	MPa
E_f^{chord}-Chord Modulus of Elasticity	1.769	GPa
ε - Max Flexural Strain	2.539	%
σ Max Flexural Strength - Reshaped	127.976	MPa
E^{chord}-Chord Modulus of Elasticity - Reshaped	1.200	GPa
ε - Max Flexural Strain - Reshaped	2.843	%

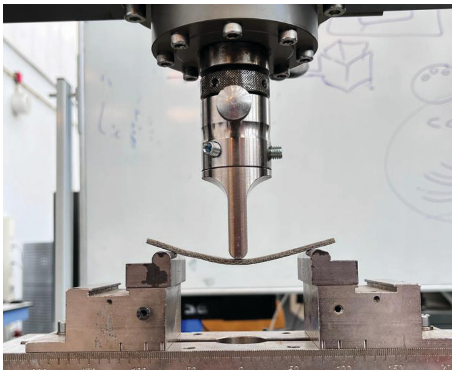
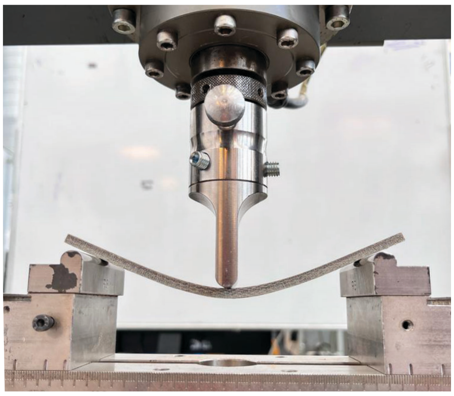


Table - C 664 - Flexural Properties Before & After Reshaping

Description	Value	Unit
σ Max Flexural Strength	128.164	MPa
E_f^{chord}-Chord Modulus of Elasticity	0.899	GPa
ε - Max Flexural Strain	2.799	%
σ Max Flexural Strength - Reshaped	106.858	MPa
E^{chord}-Chord Modulus of Elasticity - Reshaped	0.267	GPa
ε - Max Flexural Strain - Reshaped	3.426	%

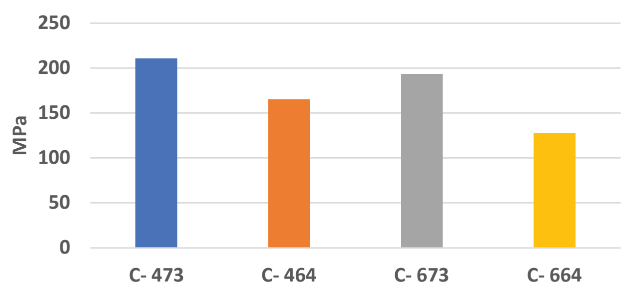


5 . 18

Comparison of Flexural Properties

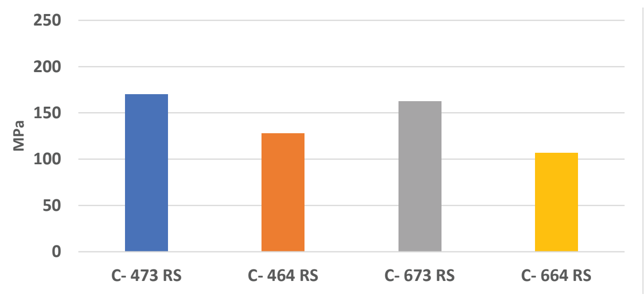
Maximum **Flexural Strength before Reshaping**

Properties before reshaping are compared below.

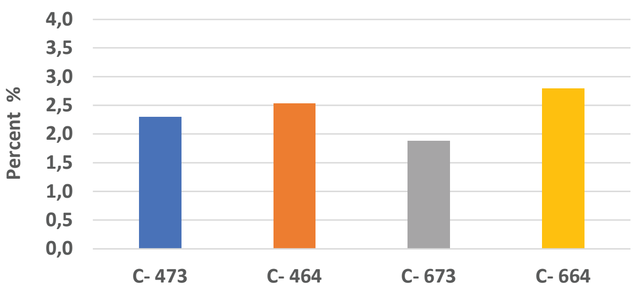


Maximum **Flexural Strength after Reshaping**

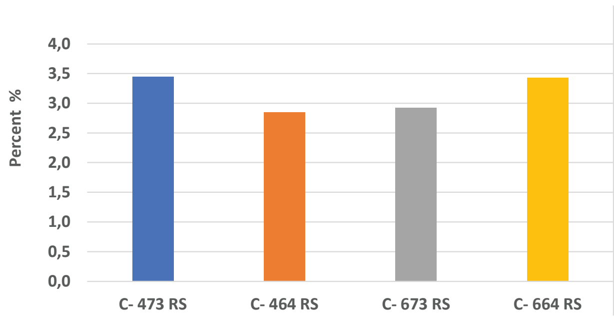
Properties before reshaping are compared below.



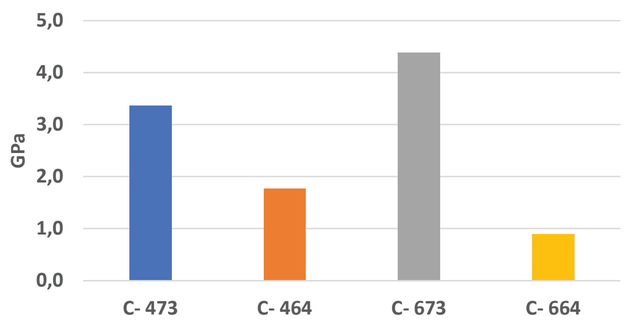
Maximum **Flexural Strain before Reshaping**



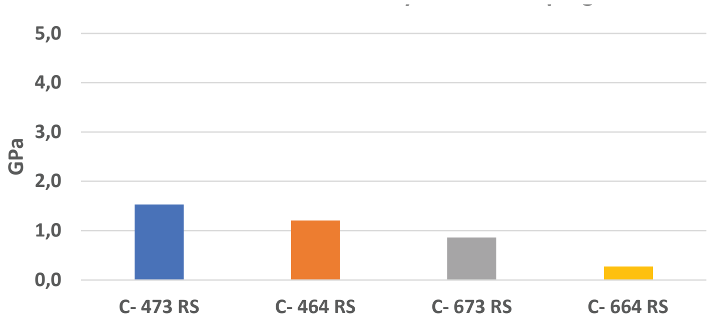
Maximum **Flexural Strain after Reshaping**



Flexural Chord Modulus of Elasticity before Reshaping

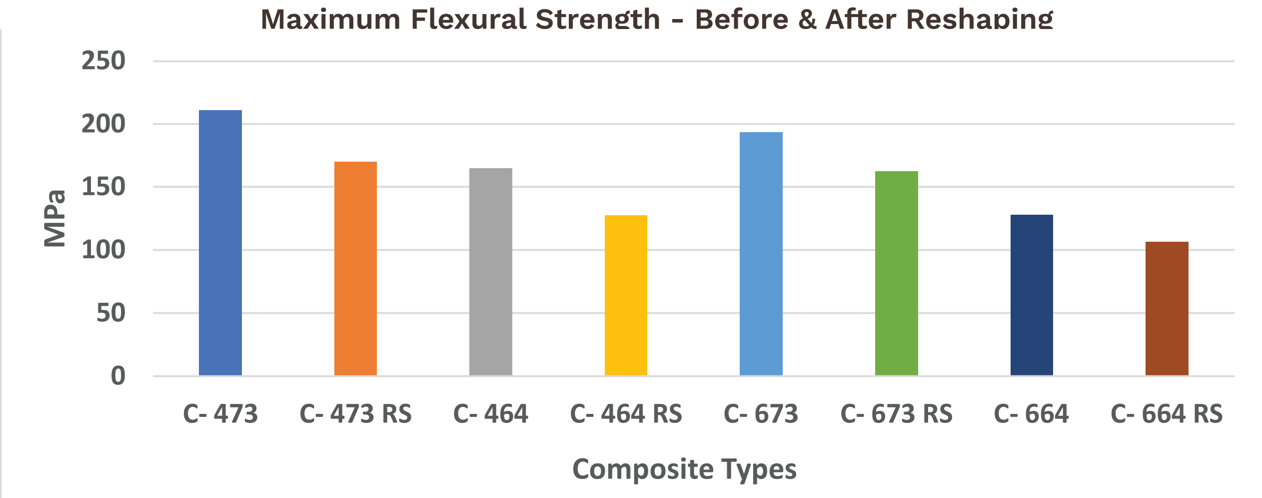


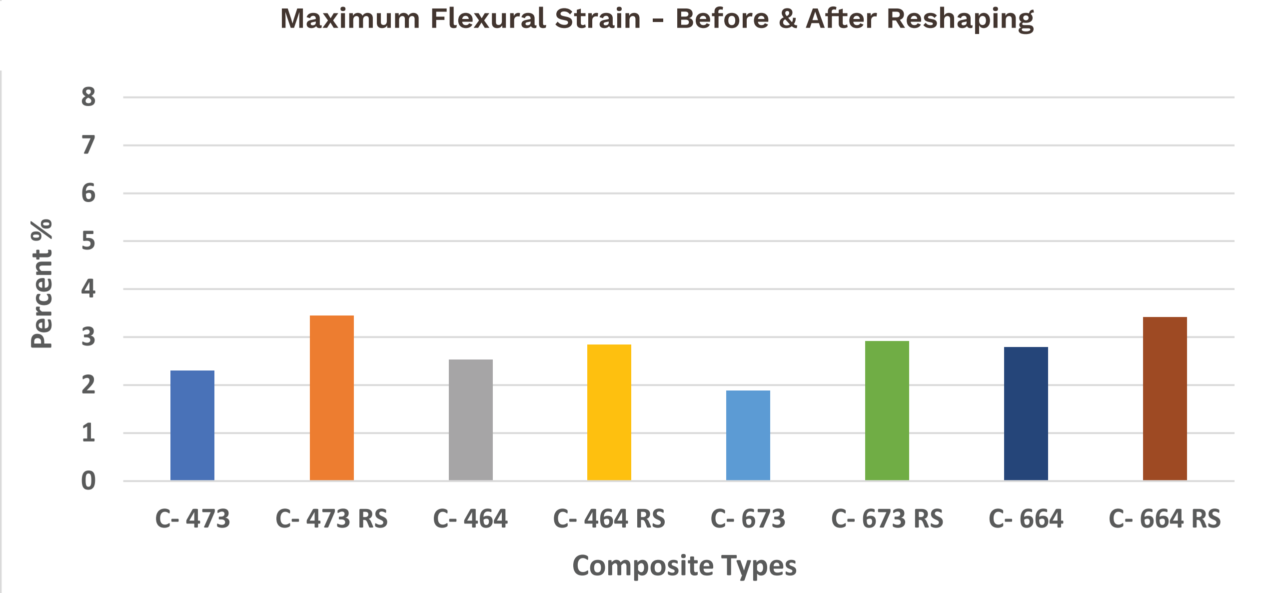
Flexural Chord Modulus of Elasticity after Reshaping

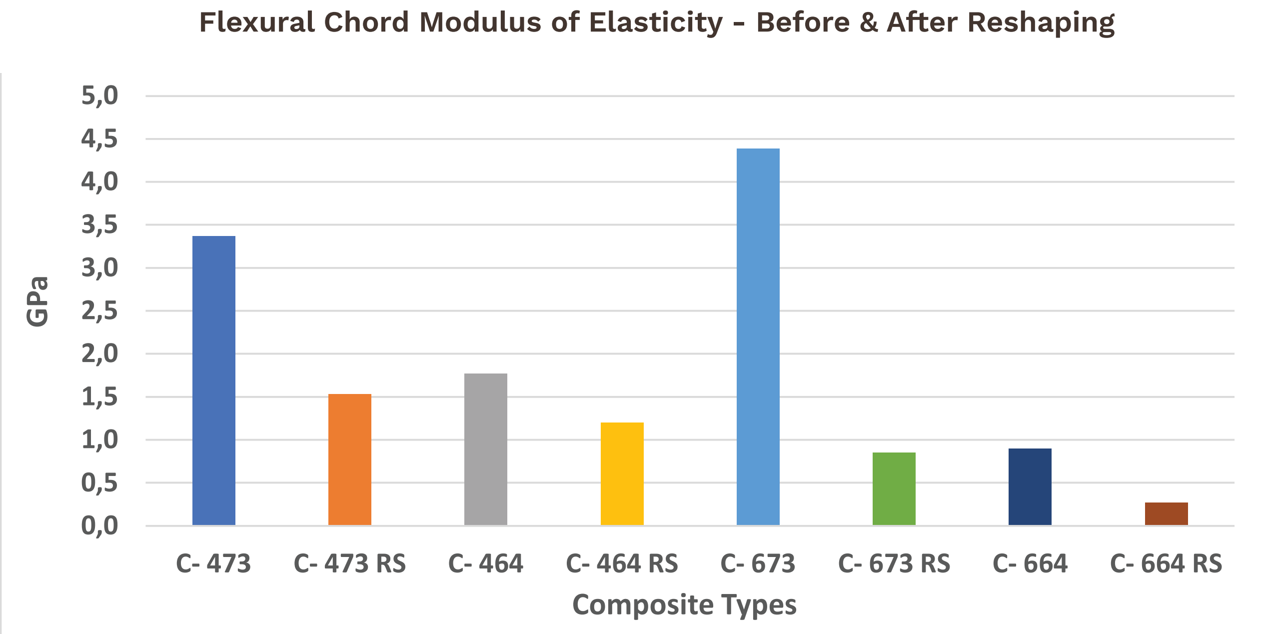


5.19

Summary of Comparisons







5.20

Discussion of Results

Impact of Reshaping on Maximum Flexural Strain

1. Maximum Flexural Strength of composites is reduced due to reshaping. Reduction varies from 16% to 22%, which is quite reasonable.

2. Though variations in a reduction in flexural strength are within a narrow band, reduction in flexural strength is marginally lower where the composite has high thickness.

   For example - reduction is lower in the case of 6 layers of flax (C673 & C664) as compared to 4 layers of flax (C473 and C464).

Impact of Reshaping on Flexural Strain

1. Flexural strain at max flexural stress level has increased in all the specimens. The increase in strain is marginally higher in thicker composite (C673 & C664) compared to C473 & 464).

   The increase in max strain is the lowest in the case of C464. Deflection in wind load case can govern external cladding panels, so this composite combination is better than the other three combinations of composites (C473, C673, C664).

2. Max flexural strain reduced for higher PLA content composite before reshaping situation. It indicates that a 60:40 Flax: PLA ratio is preferred to a 70:30 Flax: PLA ratio. It is probable that a 50:50 Flax: PLA ratio can further improve performance under flexure.

Impact of Reshaping on Flexural Strain

1. The Chord Modulus of Elasticity got reduced due to reshaping in all situations.

2. Reduction in Modulus of Elasticity is comparatively higher due to reshaping than other properties. Reduction is more pronounced in thicker composites like C673 and C664 than in C473 and C464. At maximum flexural stress level, the flexural strain has invariably increased for reshaped material.

3. Similar to changes observed during tensile test results, changes in modulus value in flexure are also more pronounced after reshaping than before.

4. There is a definite reduction in stress level for the same unit strain at the failure region.

5.21

Limitations

Limitations & Variations of Test Results

1. The test and calculation of Standard D7264 are based on beam theory, whereas the bio-composite specimens are close to plates. The difference may be significant in some cases.

2. Flexural properties also depend on testing environments, specimen thickness, and strain rate, among others.

Scientific Summary

This study analyzes the effects of reshaping on the bending or flexural properties of composite materials made from flax and polylactic acid (PLA).

Flexural Strength: Reshaping reduces the composite's maximum strength to resist bending, decreasing 16% to 22%. Interestingly, thicker composites (like those with six flax layers) show a slightly smaller reduction than thinner ones (with four flax layers).

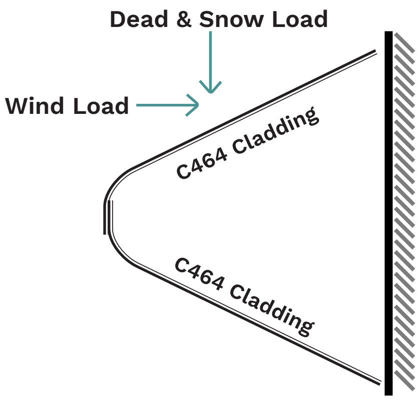
Flexural Strain: Reshaping also increases flexural strain, which represents how much a material changes in length under bending stress. This increase is slightly higher in thicker composites but less pronounced in composites with more PLA content. Thus, having more PLA (a 60:40 Flax: PLA ratio) could be more beneficial than having more flax (a 70:30 Flax: PLA ratio) in resisting deformation under bending stress. An equal mix of flax and PLA (50:50 ratio) could perform even better.

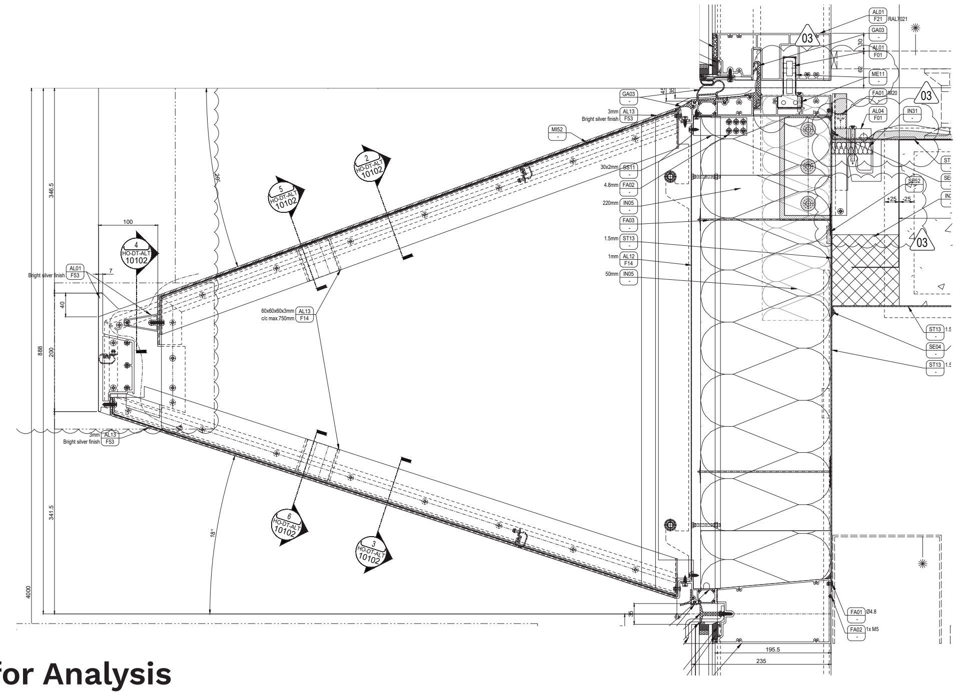
Chord Modulus of Elasticity: Reshaping decreases the composite's stiffness, with the decrease being more significant in thicker composites. This means that reshaping makes the material more prone to deformation under bending stress.

It's important to note that these findings have some limitations. The tests are based on theories designed for beam-shaped materials, while the actual composite specimens are closer to plate-shaped. Moreover, factors like the testing environment, the thickness of the specimens, and the rate of applied strain can also affect the results. These factors should be considered when interpreting the data.

5.22

C464 for Case Study





Case Study Panel Idealised for Analysis

Analysis of Cladding Panel

Objective

Evaluation of the adequacy of structural strength properties of reshaped biocomposite material for the Case Study Project cladding panel

Approach of Analysis

There are two cladding panels, each with 1 m and 0.55 m horizontal projection. A larger panel dimension is considered from the structural strength and serviceability limit perspectives of reshaped bio-composite material for evaluation purposes.

Type 1 - Horizontal projection of the panel is 1 m, and it is inclined at 19 degrees. It is considered square in size.

Type 2 - Horizontal projection of the panel is 0.55 m, and it is inclined at 34 degrees. It is considered a square in size.

Panel 1, having a larger span, is considered for checking stress and strain. Again, **C464 type biocomposite** is used for this illustrative calculation.

Cladding panel Dimensions -Type 1 - Projection 1 m

Horizontal Projection of panel	1000	mm
The angle of Inclination with horizontal	19	degree
Panel Length in either direction	1058	mm

The panel is considered as simply supported on all four edges.

Composite Panel Thickness	2.8	mm
Composite Panel Density	20	kN/m^3

5.23

Case Analysis with C464

Material Properties of C464		
F^{tu} Ultimate Tensile Strength - Reshaped	85.25	MPa
E^{chord}-Chord Modulus of Elasticity - Reshaped	1.25	GPa
ε - Ultimate Tensile Strain - Reshaped	5.59	%
σ Max Flexural Strength	165.03	MPa
E_f^{chord}-Chord Modulus of Elasticity	1.77	GPa
ε - Max Flexural Strain	2.54	%
Considering conservatively 20% reduction in flexural strength of reshaped material	0.20	
σ Max Flexural Strength - Reshaped	132.02	MPa
E_f^{chord}-Chord Modulus of Elasticity- Reshaped	1.41	GPa
ε - Max Flexural Strain - Reshaped	2.03	%

Design Loading on Cladding Panel		
Dead Load vertically downward	0.056	kN/m^2
Snow Load vertically downward	0.86	kN/m^2
Wind Load	0.766	kN/m^2
Wind can blow in any direction. It is considered normal to the panel as the most conservative approach.		
The component of Dead normal to the panel is combined with wind load.		
Design Load Combinations		
Deal Load + Wind Load		
Dead Load + Snow Load		
Dead Load + Snow Load + Wind Load		
Thermal stress is not considered at this moment.		
Design Calculation		
Dead Load normal to Cladding Panel	0.053	kN/m^2
Dead Load along the panel downward	0.018	kN/m^2
Snow Load normal to Cladding Panel	0.813	kN/m^2
Snow Load along the panel downward	0.280	kN/m^2

5.24

Discussion for Facade Compatibility

From Roark Table 11.4		
β - Roark Co-efficient for stress calculation	0.2874	
A – Roark Co-efficient for deformation calculation	0.0444	
Maximum Flexural Stress at the centre of the outer surface		
σ_{max} - Max Stress at the centre under (Dead + Snow) Load	37.56	MPa
σ_{max} - Max Stress at the centre under (Dead + Wind) Load	33.71	MPa
σ_{max} - Max Stress at the centre under (Dead + Snow +Wind) Load	68.97	MPa
Maximum deflection at the centre of the panel		
y_{max} - Max Deflection at the centre (Dead + Snow) Load	1.85	mm
y_{max} - Max Deflection at the centre (Dead + Wind) Load	1.66	mm
y_{max} - Max Deflection at the centre (Dead + Snow + Wind) Load	3.39	mm

Scientific Summary of Design Check

• The highest flexural tensile stress across all load combinations is 68.97 MPa.

• The maximum flexural stress of all tested composite combinations ranges from 128 to 211 MPa without reshaping. After reshaping, the maximum reduction in tensile stress parameters is 22% for C464.

• The maximum flexural strength of reshaped C464 material is 127.976 MPa.

• With a safety factor of 1.5, the allowable value of reshaped C464 material is calculated as 127.976/1.5, or 85.32 MPa.

• The computed maximum flexural stress value of 68.97 MPa is less than 85.32 MPa, thus it falls within the permissible limit after reshaping the material.

• The observed deformation of 3.39 mm for the panel in the case study is within the L/250 = 4.00 mm limit

Research Conclusion

Our analyses of the reshaped C464 composite reveal that even after reshaping, the material maintains its structural integrity and compliance with safety standards.
The computed maximum flexural stress of 68.97 MPa remains within the allowable limit of 85.32 MPa, and the observed panel deformation of 3.39 mm aligns well within the established limit.

These findings validate the performance and resilience of reshaped C464 composite, providing crucial insights for its potential applications and continued study.

5.25

Outdoor Weathering Test

Aim
The aim is to observe the initial degradation and weathering effects on the material, including changes in visual appearance and physical properties.

Significance
This test exposes the material to real-world weather conditions & elements such as sunlight (UV radiation), rain, temperature variations, and more, providing direct information on how the material will respond over time and it's suitability for outdoor use.

Outdoor Weathering for Plastics ASTM D1435
The biocomposite's weathering properties in this research were evaluated following the guidelines outlined in ASTM D1435, a recognized standard for conducting outdoor weathering tests of plastic non-metallic materials.

Duration of Test
The test was carried out at outdoor conditions from 26th of May 2023 to the 26th of June 2023 for a period of 4 weeks, at Delft, South Holland, Netherlands.

Conditioning
Specimens were untreated, so were exposed to the outdoor conditions without any protective coatings or artificial conditioning.

Exposure Configuration
The test samples are mounted on an outdoor rack, facing the equator at a 45-degree angle. This configuration ensures maximum exposure to sunlight, facing south-east sun.

Protocol Setup

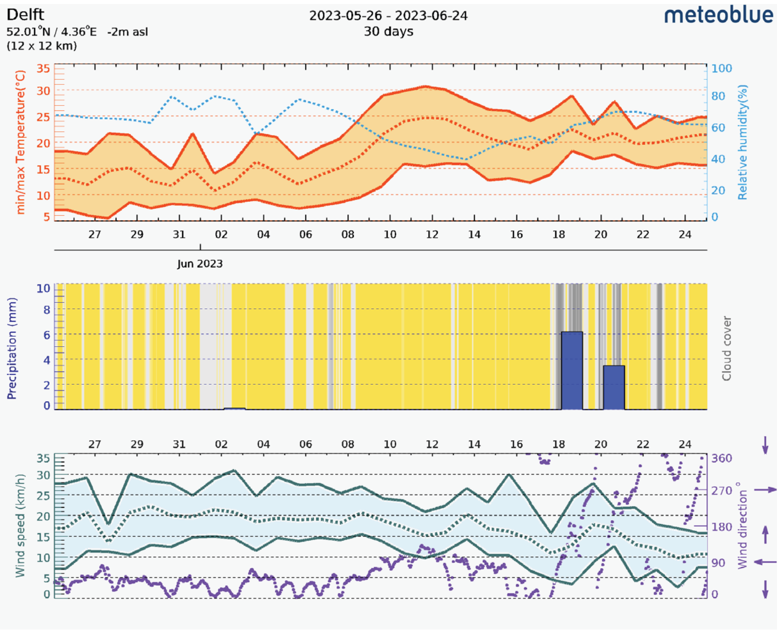


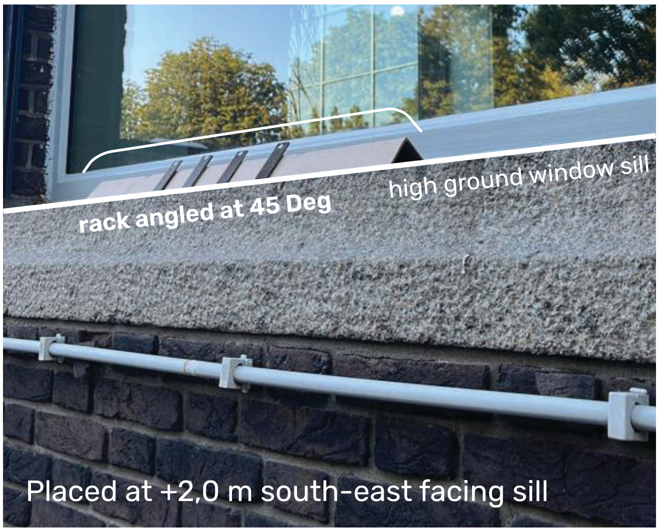
Fig: Temperature History of Delft in 2023 May to June

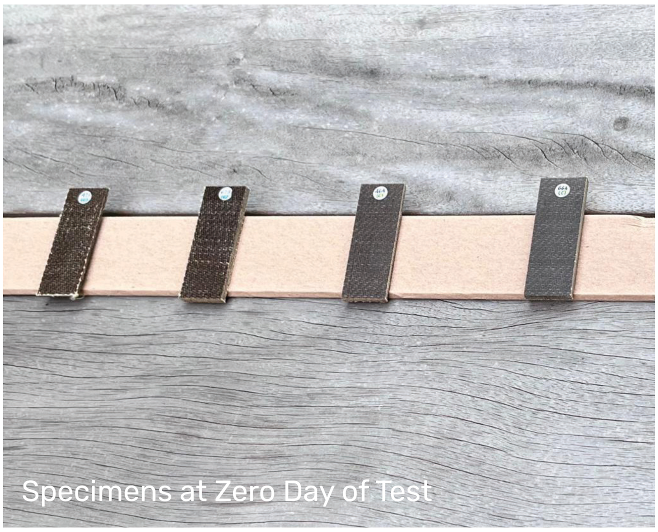
Ongoing Test Summary

The period of 4 weeks was peak summer season with significant sunlight exposure on the specimens, along with longer daytime hours. The specimens also recieved rainfall and showed significant weathering effects at the mark of 2.5 weeks.

Micro & Macro Effects
For noting the differences, observations like visual-tactile differences, dimensions and weight of the specimens were recorded before and after the outdoor weathering.

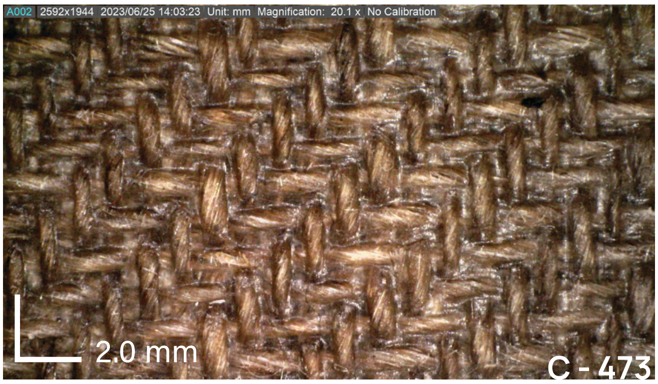
To gain further insight of influence from the environmental effects , micrographs of unweathered specimens are compared with the exposed specimens.

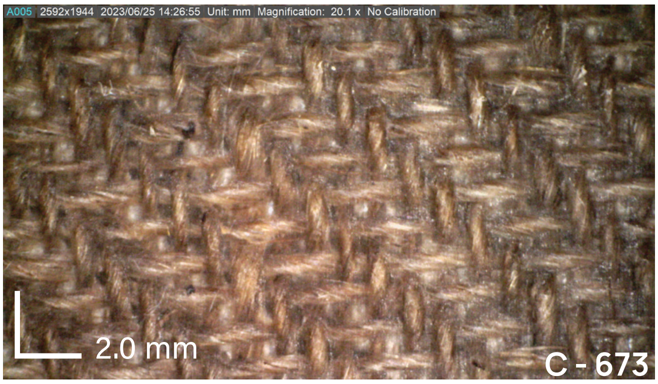


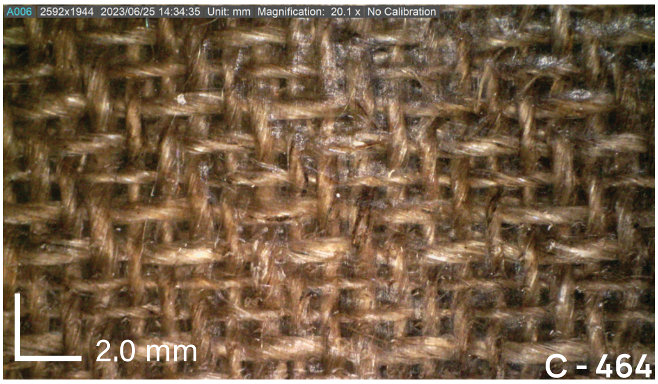


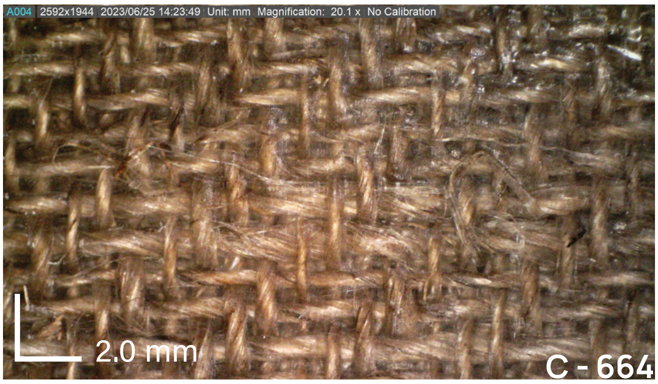
Specimens after 4 Weeks Outdoor Exposure

Original Specimens (Unweathered)

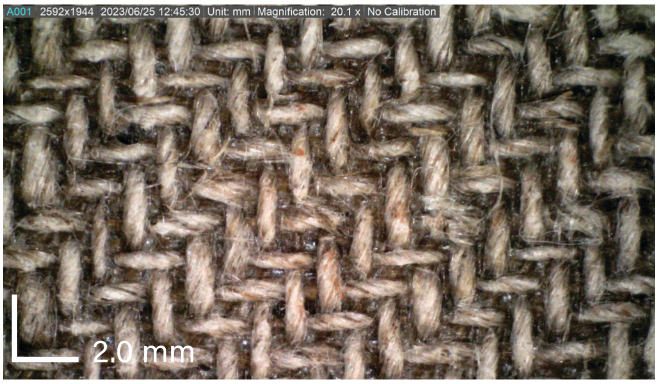


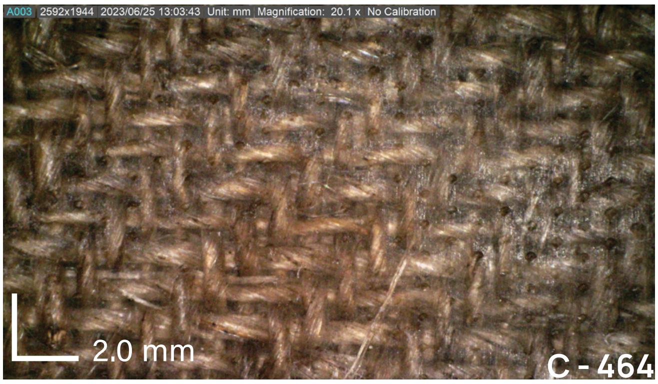


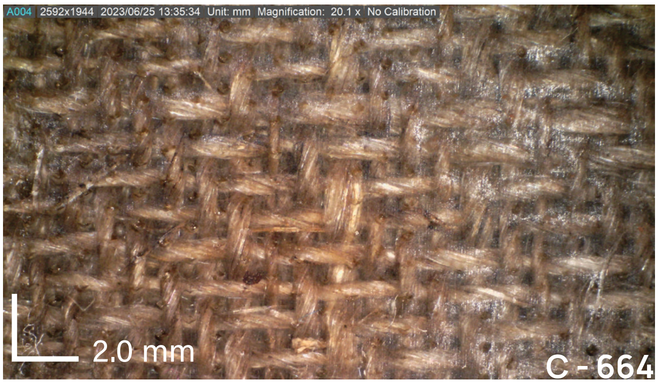




Specimen Micrographs Post Exposure







5.26

Weathering Test Results

Dimensions of Samples before test

The test samples data pre-exposure.

sample ID	length mm	width mm	area m^3	thk mm	volume m^3	initial weight grams
C-473	70	25	1750	2,01	3500	17,02 g
C-673	70	25	1750	3,03	5250	27,84 g
C-464	70	25	1750	2,85	4987,5	22,94 g
C-664	70	25	1750	4,50	7875	34,19 g

Dimensions Post Outdoor Weathering

The test samples data pre-exposure.

sample ID	length mm	width mm	area m^3	thk mm	volume m^3	test weight grams
C-473	70	25	1750	2,12	3500	17,21 g
C-673	70	25	1750	3,03	5250	28,10 g
C-464	70	25	1750	2,85	4987,5	23,02 g
C-664	70	25	1750	4,50	7875	34,30 g

Visual / Tactile Changes

The 473 and 673 micrographs show pronounced visual changes, with color fading likely due to UV exposure, and surface roughness from exposed, frayed fibers caused by PLA layer erosion.

In contrast, the 464 and 664 samples demonstrated minor visual alterations and maintained smoother textures, although microscopic examination revealed potential UV-induced scratches. These samples, however, resisted substantial color fading, suggesting better weathering resistance.

Initial versus Post Exposure Weight

70:30 mass ratio, showed a greater weight gain, likely from moisture uptake through their exposed facia. However, thickness changes were uniformly minimal across all samples. With the exception of the more vulnerable 473 composite, all other composites saw weight gain < 2%

Signs of Growth

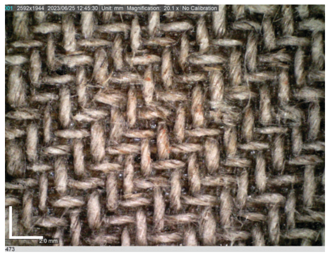
No signs of biological decay or growth on any specimens, indicating their resilience against bio-degradation. This was confirmed both visually and under microscopic examination.

Discussion of Results

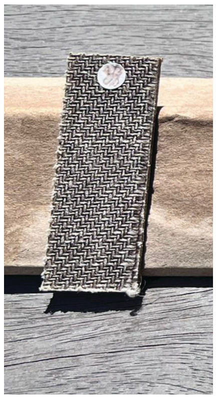
Comparative Analysis

We examine the highest & lowest degrees of change.

Unexposed 473 **Weathered 473**



Length = unchanged
Width = unchanged
Thickness = 3.48 % increase
Weight = 1.12 % increase

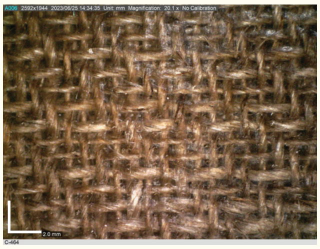


Most Weathering Observed

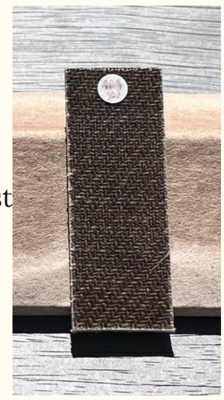
This sample demonstrated the most weathering. Most apparent changes were visual and tactile - the color faded likely due to UV exposure, while the material surface became rough due to exposed fibers.

The fraying & fade might be a result of the thin PLA layers (70:30 mass ratio) wearing away, leaving the flax fibers unprotected.

Unexposed 464 **Weathered 464**



Length = unchanged
Width = unchanged
Thickness = 1.7 % increase
Weight = 0.35 % increase



Least Weathering Observed

This sample experienced the least weathering. Only minor visual changes were observed, with some scratches visible on the micrographs, possibly due to UV degradation. There was minimal color fading due to more PLA.

The fraying & fade might be a result of the thin PLA layers (70:30 mass ratio) wearing away, leaving the flax fibers unprotected.

5.27

Water Absorption Test

Objective
The water absorption test determines the quantity of water that the material can absorb under specific conditions. This includes changes in weight, physical properties, and appearance due to water uptake.

Significance
ASTM D5229 measures the water absorption, loss, and diffusion of plastics when immersed in water or exposed to a humid environment. These characteristics impact the material's electrical properties, mechanical strength, and dimensions, significantly affecting overall performance.

Standard Test Method for Moisture Absorption Properties of Polymer Matrix Composite Materials ASTM D5229

In this research, the biocomposite's water absorption characteristics were examined using ASTM D5229, a standard procedure for water absorption, loss, and diffusion of polymer matrix composites.

Time of Immersion
The test was carried out in a controlled environment over a period of 24 hours, as specified in the ASTM D5229 standard.

Specimen Preparation
Prior to immersion, specimens were dried in a simple oven at a temperature of 50 ± 5° for 1 min. Post drying the samples were cooled till room temperature. This was to ensure that all water content prior to the test is effectively removed, creating a reliable baseline for measuring water absorption.

Edge Conditioning
In materials with differing moisture absorption rates, edge effects should be minimized by sealing edges. Weight was recorded before and after sealing to measure the added mass. The adhesive used shouldn't absorb significant moisture to affect the results.

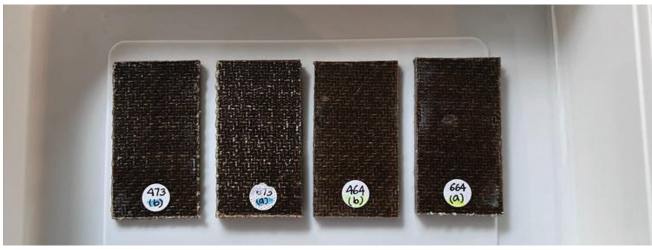
Protocol Setup

Excerpt from D570

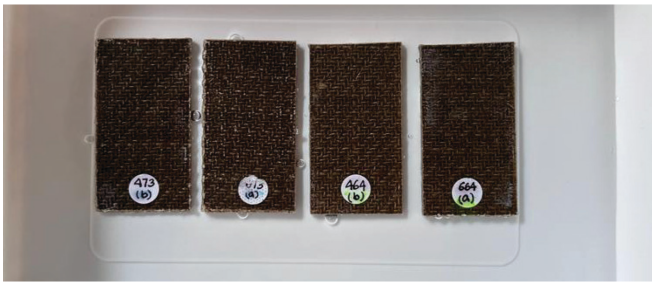
10.1.5 Percentage increase in weight during immersion, lculated to the nearest 0.01 % as follows:

$$\text{Increase in weight, \%} = \frac{\text{wet weight} - \text{conditioned weight}}{\text{conditioned weight}} \times 100$$

Dry Samples



Post Immersion Setup **Duration = +0 Hours**

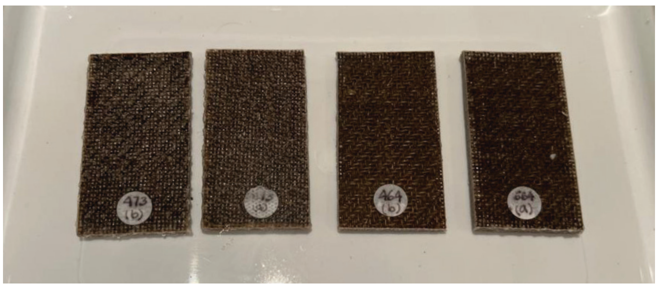


Dimensions of Samples before test

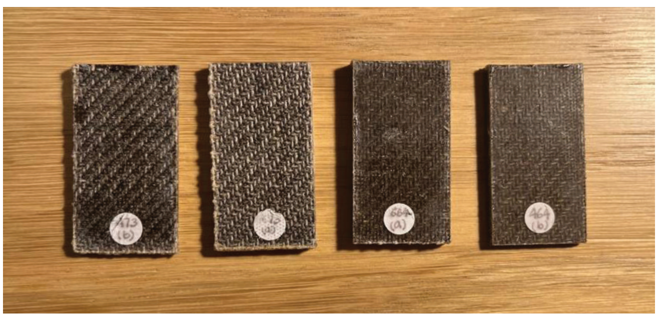
The test samples data pre immersion.

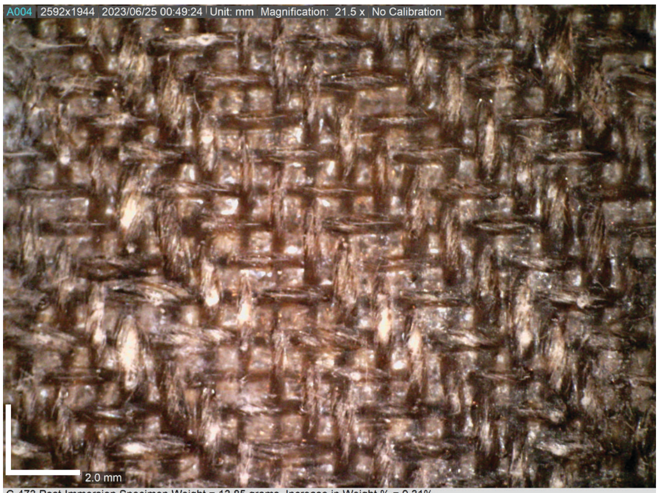
sample ID	length mm	width mm	area m³	thk mm	volume m³	initial weight grams
C-473	46	25	1150	2,01	2300	12,56 g
C-673	46	25	1150	3,03	3450	18,64 g
C-464	46	25	1150	2,85	3220	16,77 g
C-664	46	25	1150	4,50	5175	22,54 g

Post Immersion Setup **Duration = +72 Hours**



Post 72 Hours Immersion in Water Specimens





C-473 Post-Immersion Specimen Weight = 13,85 grams Increase in Weight % = 9,31%

C-673 Post-Immersion Specimen Weight = 20,10 grams Increase in Weight % = 7,26%

C-464 Post-Immersion Specimen Weight = 17,33 grams Increase in Weight % = 3,23%

C-664 Post-Immersion Specimen Weight = 23,42 grams Increase in Weight % = 3,75%

Discussion of Results

sample	length	width	area	thk	volume	water weight
C-473	47	25	1175	2,95	3466	13,85 g

C-473 70% Flax 30 % PLA 4 Layers

Initial Weight	=	12.56 grams
Post Immersion Weight	=	13.85 grams
% Increase in Weight	=	9.31 %

The high % increase in weight can be attributed to the high moisture absorption by the exposed fibers on the composite's surface. The prevalence of these exposed fibers is due to the lower proportion of PLA in the composite.

sample	length	width	area	thk	volume	water weight
C-673	47	25	1175	4,01	4712	20,12 g

C-673 70% Flax 30 % PLA 6 Layers

Initial Weight	=	18.64 grams
Post Immersion Weight	=	20.12 grams
% Increase in Weight	=	7.35 %

C-673 experienced the second highest weight increase of 7.35% post immersion. The weight & dimensional gains are primarily due to the absorption of moisture by the exposed fibers on the surface. Despite more layers than C-473, a similar phenomenon is observed due to the same PLA mass ratio, contributing to the presence of exposed fibers.

sample	length	width	area	thk	volume	water weight
C-464	46	25	1150	2,9	3335	17,33 g

C-464 60% Flax 40 % PLA 4 Layers

Initial Weight	=	16.77 grams
Post Immersion Weight	=	17.33 grams
% Increase in Weight	=	3.23 %

C-464 displayed the lowest weight gain after immersion, with an increase of 3.23%, likely attributed to the higher PLA content of 40%. The 60:40 ratio provides additional coating to the composite's surfaces, thereby reducing moisture absorption or interaction with the fibres & ultimately limiting the post-immersion weight gain.

sample	length	width	area	thk	volume	water weight
C-464	46	25	1150	4,5	5175	23,42 g

C-664 60% Flax 40 % PLA 6 Layers

Initial Weight	=	22.54 grams
Post Immersion Weight	=	23.42 grams
% Increase in Weight	=	3.75 %

C-664 had a low weight increase of 3.75% post-immersion. The % is similar to the C-464, attributing to the higher PLA content, which effectively protects the composite's surface fibers, reducing their capacity to absorb moisture. Despite having more layers than C-464, the similar PLA percentage results in a comparably limited post-immersion weight gain.

5.28

Derived Insights: Water & Weather

Scientific Summary from :

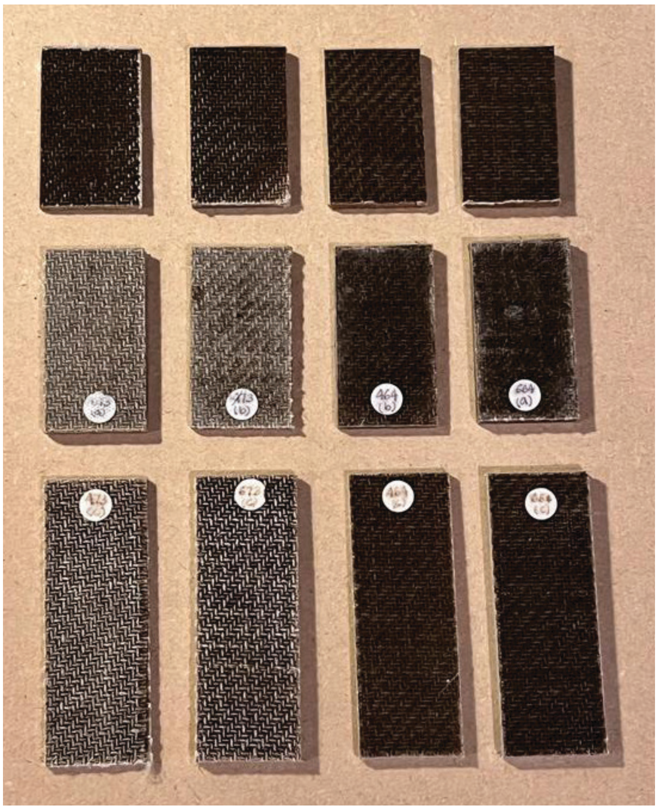
Outdoor Weathering Test Results
Water Absorption Test Results

Post these two tests, it is understood that the proportion of Polylactic Acid (PLA) plays a pivotal role in determining the material's weathering resistance and moisture absorption.

Role of PLA in Resistance
C464 and C664 with a higher PLA proportion (40% in our case) showed greater resistance to environmental changes. The 60:40 ratio composites exhibited fewer visual changes, maintained a smoother texture, and displayed less color fading compared to those with a lower PLA proportion.

This highlights the PLA's protective function, shielding the exposed flax fibers and thereby mitigating adverse environmental effects such as UV degradation and moisture absorption.

Feasibility Check
These tests were merely an indicator & have confirmed the viability of the biocomposites in an outdoor application, for which the composites with **higher PLA % show promise.**



Recommended Tests :

Accelerated Ageing Tests
Outdoor Fixed Rack Exposure Test

The implementation of further tests like accelerated aging tests & fixed rack test is crucial. These would offer insights into the material's long-term performance, simulating the wear and tear due to weathering over a more extended period.

Context Specific Iterative Tests
The results indicate that the Flax-PLA performance could vary significantly in different environmental settings. In conditions where exposure to UV light and moisture is higher, materials with a higher PLA content would likely fare better, however would need to be balanced with the material's other required characteristics, which could be influenced by the PLA proportion.

This underlines the necessity for context-specific material testing to optimize performance based on environmental factors. The insights gained reinforce the importance of iterative testing and continuous research in this area to create materials that are both durable and environmentally friendly.

Outdoor Fixed Rack Exposure Test

Accelerated Ageing Test Chamber

5.29

Micrograph Documentation

Objective
To understand the material level changes occurring during the shaping cycles of the Flax+PLA biocomposite.

Relevance
Micrographs are high-resolution images captured through microscopy. These will enable the examination of the biocomposite's facia structure, fiber-matrix interactions, and any alterations caused by the shaping process.

Procedure & Tool Used
The tool used was a Digital Microscope by Dino-Lite Europe, mounted on a test stand, that could be calibrated as per magnification and resolution.

The procedure was carried out according to the software instructions by the microscope manufacturers.

Micrograph Analysis at Each Cycle
The test was carried out in indoor conditions on the 20th of June 2023 at Delft, South Holland, Netherlands, under indoor lighting conditions.

Conditioning
All specimens were C-464 panels that were bent to represent all 5 stages from the aforementioned shaping cycles of this research project. Total 5 panels were studied, and bent for this documentation.

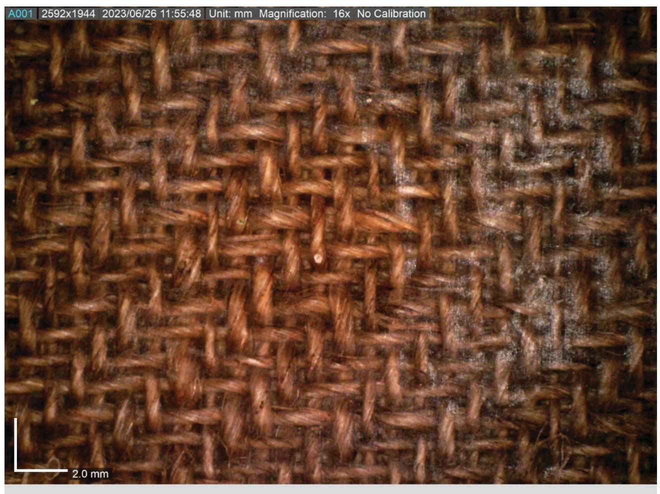
Magnification
The magnification was 16X at a 2 mm scale maintained across the samples. This allowed us to compare the bending region alterations at every stage of shaping.

Phase 1

Original State - **Flat**

1

Microscopic Close Up of Original State



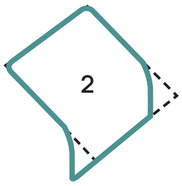
Panel 1 represents **Original Flat Sheet State**

Microscopic examination of the C464 composite reveals a **high degree of uniformity** and integration. The **uniform coloration** indicates excellent PLA penetration into the flax fabric, with no discernible variation in fibre appearance.

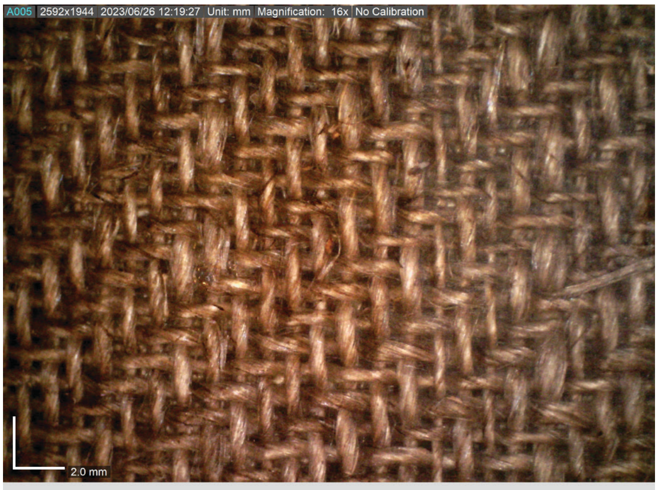
This suggests effective resin distribution during manufacturing. The surface of the composite is smooth, lacking any visible disruptions, pointing towards a high-quality, well-consolidated product.

Phase 2

Flat › **Bent**[1]



Microscopic Close Up at Bending Region



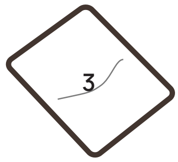
Panel 2 represents **First Shaping Bend**

Panel 2, subjected to the initial forming cycle and bent to achieve a curvature with a radius of 0,6 m, exhibits comparable characteristics to Panel 1. Despite the 20-degree deviation from the horizontal reference during bending, there is hardly any noticeable variation in fibre uniformity.

This suggests the process **effectively maintains the integrity** of the composite structure. The absence of disruptions or colour fading in the bending region further attests to the robustness of the flax-PLA composite when subjected to shape modification.

Phase 3

Flat › Bent[1] › **Flattened**[1]



Microscopic Close Up at Flattened Region

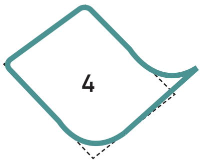
Panel 3 represents **Flattening the Curve**

Panel 3, representing the phase of flattening the curve introduced in Stage 2, exhibits the onset of subtle changes in the composite structure.

Initial signs of PLA hardening and colour fade, were paralleled by a slight change in fibre colour. Despite these transformations, the panel largely retained its shape conformity, albeit less perfectly compared to its original state. Although, it didn't revert to the Original state, the application of equivalent time and heat allowed the panel to largely relinquish its curvature, resulting in a near flat state, presence of minor crease imprinted by the bend, but overall the material was viable for further bending.

Phase 4

Flat > Bent^1 > Flat^1 > **Bent^2**



Microscopic Close Up at Bending Region

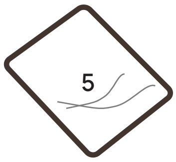
Panel 4 represents **Second Shaping Bend**

The reversing and bending of the composite in the opposing direction, revealed more distinct variations under microscopic examination. This stage represents the second shaping cycle.

Unlike previous stages, a pale fade is discernible in the bending region, potentially due to local fibre tensioning, PLA phase transitions from melting to hardening, straining effects, or localized strains. This marked a pronounced difference from both the original and earlier bent states, indicating a more significant impact on the composite structure in this stage of manipulation.

Phase 5

Flat > Bent^1 > Flat^1 > Bent^2 > **Flat^2**



Microscopic Close Up at Flattened Region

Panel 5 represents **Final Flattening**

Panel 5 depicts the final stage of flattening, marking the second return to the composite's original flat sheet phase. The panel exhibits a clear material history of bending, evident at both microscopic and macroscopic levels.

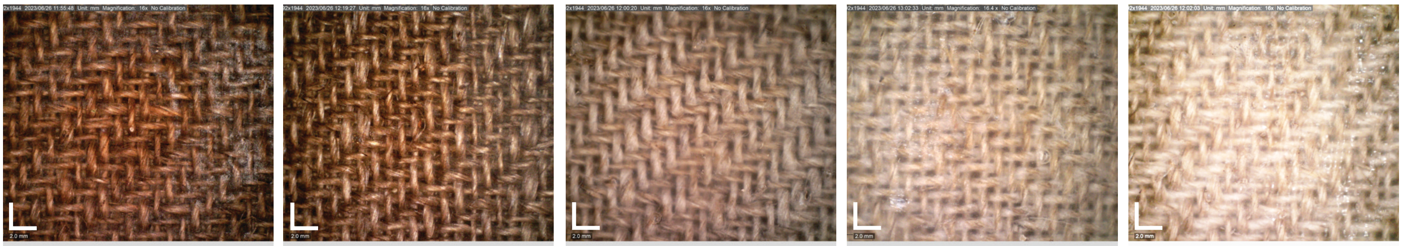
The most significant degree of colour fading is observed at this stage, with the resin displaying a cloudy appearance in the micrograph as compared to the original state, especially in the bending region, and fibres appearing paler or tensioned. Additional creasing is visible on the panel, and a residual bend is present, indicating the material's memory of the forming processes it underwent.

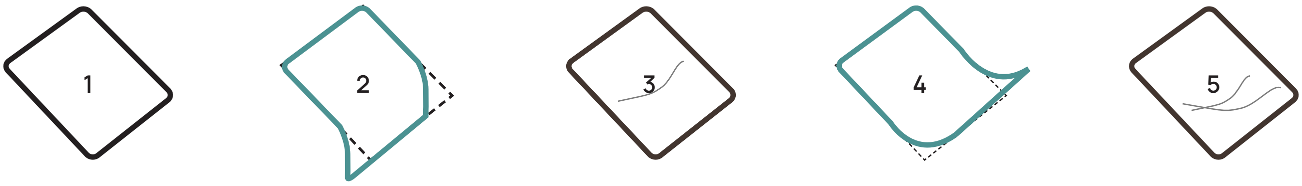
5 . 30

Discussion

Micrographic Evidence

In focus: The Bending Region across Shaping Cycles





The initial state of the composite (Panel 1) displayed high uniformity and effective integration of PLA and flax fibres, illustrating the efficacy of the production process. Despite undergoing the initial bending process (Panel 2), the composite retained its structural integrity and uniformity, which is a testament to its resilience.

The subsequent stages, however, began to reveal changes in the composite structure. During the flattening process (Panel 3), initial signs of PLA hardening and fading were noted, hinting at the material's reaction to the applied forming forces. Nevertheless, the panel maintained a near-flat state suitable for subsequent forming processes, demonstrating the material's malleability.

Notably, when the composite was subjected to an opposing direction of bending (Panel 4), more pronounced changes emerged. The appearance of pale fading in the bending region suggested local fibre tensioning, phase transitions in PLA, or localized fatigue - factors indicating the onset of material limitations.

The final stage of flattening (Panel 5) revealed the most visible changes, with the highest degree of fading, a cloudy appearance of the resin, and visible tensioning of the fibres. Despite this, the panel did retain some level of its shape memory.

Scientific Reflection

This study of bending and examining each stage highlights the material's ability to endure manipulation, whilst also revealing its structural limits over extensive processing cycles. Repeated shaping cycles do result in appreciable changes in its structure and appearance, though none of these alterations cause any permanent changes anc can be hypothetically remanufactured to the original state by heating till PLA's melting point and compressing at the manufacturing pressure. The material can at that point be ready for further shaping cycles, however, this needs to be empirically tested in future.

Summary

This chapter presented a comprehensive analysis of effects of reshaping on the mechanical properties of flax-PLA composite materials.

The study involved various tests, starting with tensile testing and flexural testing, to track the material behavior and patterns before and after reshaping.

The aim was to evaluate the impact of the reshaping process on the performance of the biocomposite and determine its suitability for end-use applications.

The results of the study showed that even after reshaping, the material maintains its structural integrity and compliance with safety standards. However, the tensile failure was localized within the bending regions for the reshaped specimens, while all the unshaped specimens demonstrated failure centrally.

For a more comprehensive understanding of the material's behaviour, this study documented tests like water absorption tests and outdoor weather testing, which exposed the material to real-world weather conditions and elements, providing direct information on how the material will respond over time and its suitability for outdoor applications.

The study also documented micrographs at different shaping cycles to understand the microscopic alterations in the material at the bending region. Each stage highlightsedthe material's ability to endure manipulation, whilst also revealing its structural limits over extensive processing cycles.

The findings validate the resilience of reshaped flax-pla composites, providing crucial insights for their potential applications and continued study.

06

future potential research **evaluation**

This chapter encapsulates the journey of benchmarking **bio-composites** with conventional case, assessing the lifecycle **impact**, and envisioning sustainable, **circular** futures.

6.1

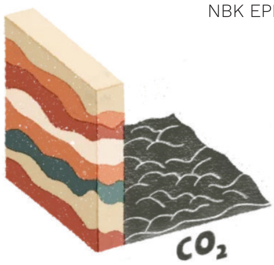
Sustainability Evaluation

Embodied Carbon

Embodied carbon refers to the total greenhouse gas emissions produced during the lifecycle of a built asset, encompassing extraction, manufacturing, transportation, assembly, and potentially maintenance, replacement, deconstruction, disposal, and end-of-life stages. However, accurately calculating this for facade systems is a complex task due to the intricacies of each lifecycle stage.

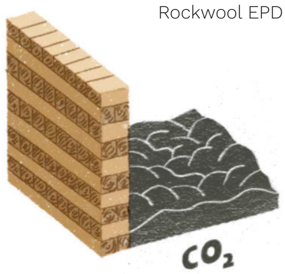
Embodied Carbon Stages A1 - A3

Ceramic Tile
NBK EPD



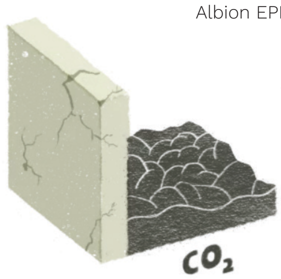
90 kg of CO_2e/m^2

Mineral Wool
Rockwool EPD



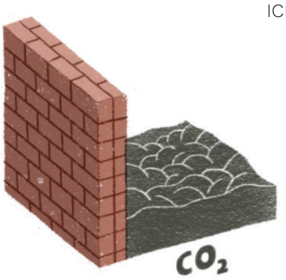
11 kg of CO_2e/m^2

Limestone
Albion EPD



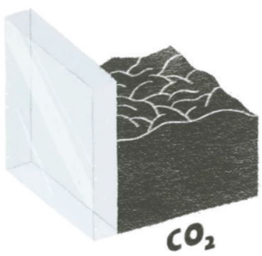
15.5 kg of CO_2e/m^2

Brick with Mortar
ICE



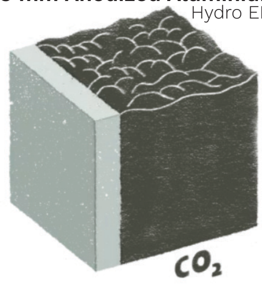
40.5 kg of CO_2e/m^2

6+6 Double Lam DGU
Saint Gobain EPD



95 kg of CO_2e/m^2

3 mm Anodized Aluminium
Hydro EPD



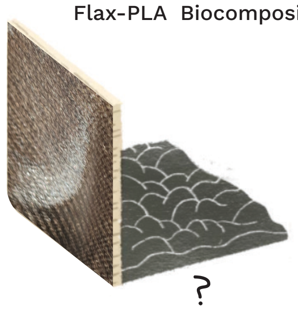
79 kg of CO_2e/m^2

Benchmarking Flax-PLA Biocomposites

To ascertain the environmental benefits of using Flax-PLA Biocomposites produced in this research as alternatives to Aluminium cladding panels, it is essential to quantify the effect of the developed material and product on the environment.

This thesis will present an estimate assessment of the carbon dioxide emissions associated with the entire lifecycle of the fibre reinforced biocomposite panels, tracing the journey from extraction and processing of raw materials, manufacturing of the panels, their operational use cycles and ultimately their disposal to return to biological cycles.

Flax-PLA Biocomposite



xxxx kg of CO_2e/m^2 of Facade Surface Area

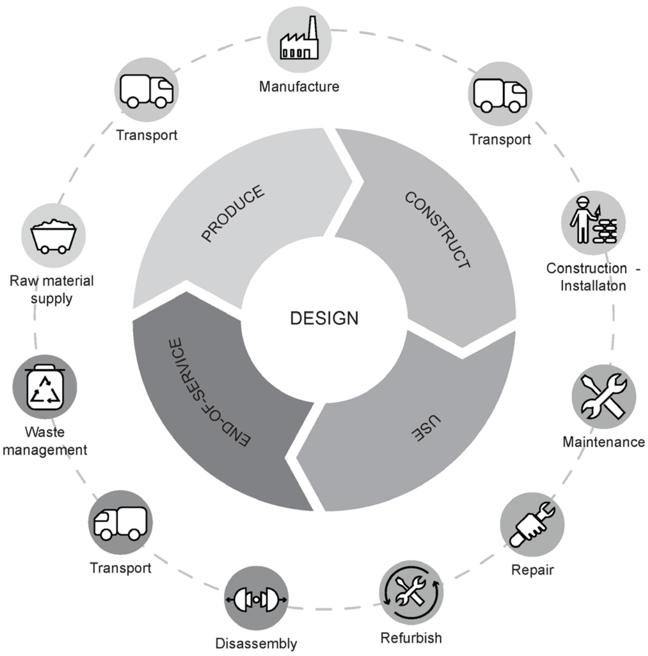


Figure: Diagram depicting Life Cycle of a Product in a Circular Economy for a Sustainable Built Environment. (TU Delft OpenCourseWare, 2020)

6.2

Carbon Footprint Assessment

Approach **Simplified LCA Study**

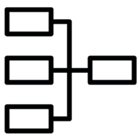
The following is a quantitative assessment of the Global Warming Potential of Flax-PLA biocomposite cladding panels, visualizing the GHG emissions from all stages of the product lifecycle.
The life cycle assessment is carried out in four main steps :

Step 1
Goal and Scope Definition

This includes clearly stating the purpose for conducting the LCA, identifying the intended audience, and outlining the specific applications, and expected results of the study.

The scope defines the functional unit for this research GWP [kg CO_2 equivalent], reference flow, impact categories, and system boundaries, which together form a comprehensive blueprint of the product life cycle, from raw materials acquisition to end-of-life.

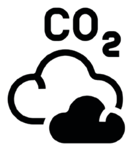
Step 2
Life Cycle Inventory (LCI)



Once the system boundaries are defined, the next step is to create a detailed inventory of all materials and processes, and their corresponding environmental inflows (e.g., raw materials, energy inputs) and outflows (e.g., emissions, waste).

At this step, a system tree is created to determine the processes according to collected data, and visualise all the inflows and outflows.

Step 3
Life Cycle Impact Assessment (LCIA)



This step analyses and evaluates the potential environmental impact category ascertained during scope definition, in this case the Global Warming Potential.

The impact assessment is to translate the inventory data from the flowchart of LCI and calculate the cumulative impact of the product from the data collected.

Step 4
Interpretation

Final step is to analyze the results, identify the stages or activities areas of the product's lifecycle with the most impact on the environment and make recommendations for reducing the carbon footprint.

To conclude the assessment, this research will determine how the flax-PLA biocomposite measures as compared to Aluminium Cladding in terms of GHG emissions and CO_2 savings.

Outcome

Through this exercise, we can find answers for our hypothesis of biocomposites being a sustainable and circular variant than the traditional aluminium cladding panel, reflecting all the life cycle stages and their consequent effects on the environment.

6.3

Goal and Scope Definition

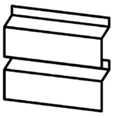
The first step of setting a clear goal and a well-defined scope lays the foundation for the entire assessment.

1. GOAL

The goal of this particular study is examine the Flax-PLA Biocomposite and compare the environmental impacts with traditional Aluminium cladding panels to quantify the effects of this biocomposite's product on an environmental context.

Target Audience

The results of this study will be primarily useful for innovators, architects, engineers, policymakers, and manufacturing industries seeking sustainable material alternatives in the building sector.

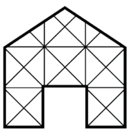


Intended Application

The intended end-use application for this assessment would be external **facade cladding** system with conventional support systems equipped with demountable connections. For the purpose of this assessment, it is assumed to be a demountable facade cladding design, and for estimation, only the cladding panels will be studied.

2. SCOPE

The assessment will be an **estimation** of the impact and only the cladding panels will be studied across it's varying lifecycle stages for the intended use as panels. The scope of the study is to derive an **approximation** of eco- impact rather than an absolute precise figure. The scope includes the material origins to processing, manufacturing of the product and its use cycles, till the end of life potential.

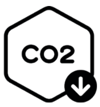


Functional Unit

This refers to the base unit used for comparison in the study. For our Flax-PLA Biocomposite cladding panels, the functional unit is defined as **1 m^2 of the facade surface area**.
Concerning the cultivation of flax, the outputs refer to 1 tonne of flax fibre.
For the manufacturing of PLA, the output is 1 tonne of Poly-Lactic Acid.

System Boundaries

The geographical area of assessment is Netherlands and the countries around Western Europe, as the raw materials were sourced and processed from these countries.
1 square sample of Flax-PLA with l = 1000 mm, w = 1000 mm thk = 2.95 mm
Weight = 8.085 kilograms Density = 2.74 g/cm^3



Impact Category

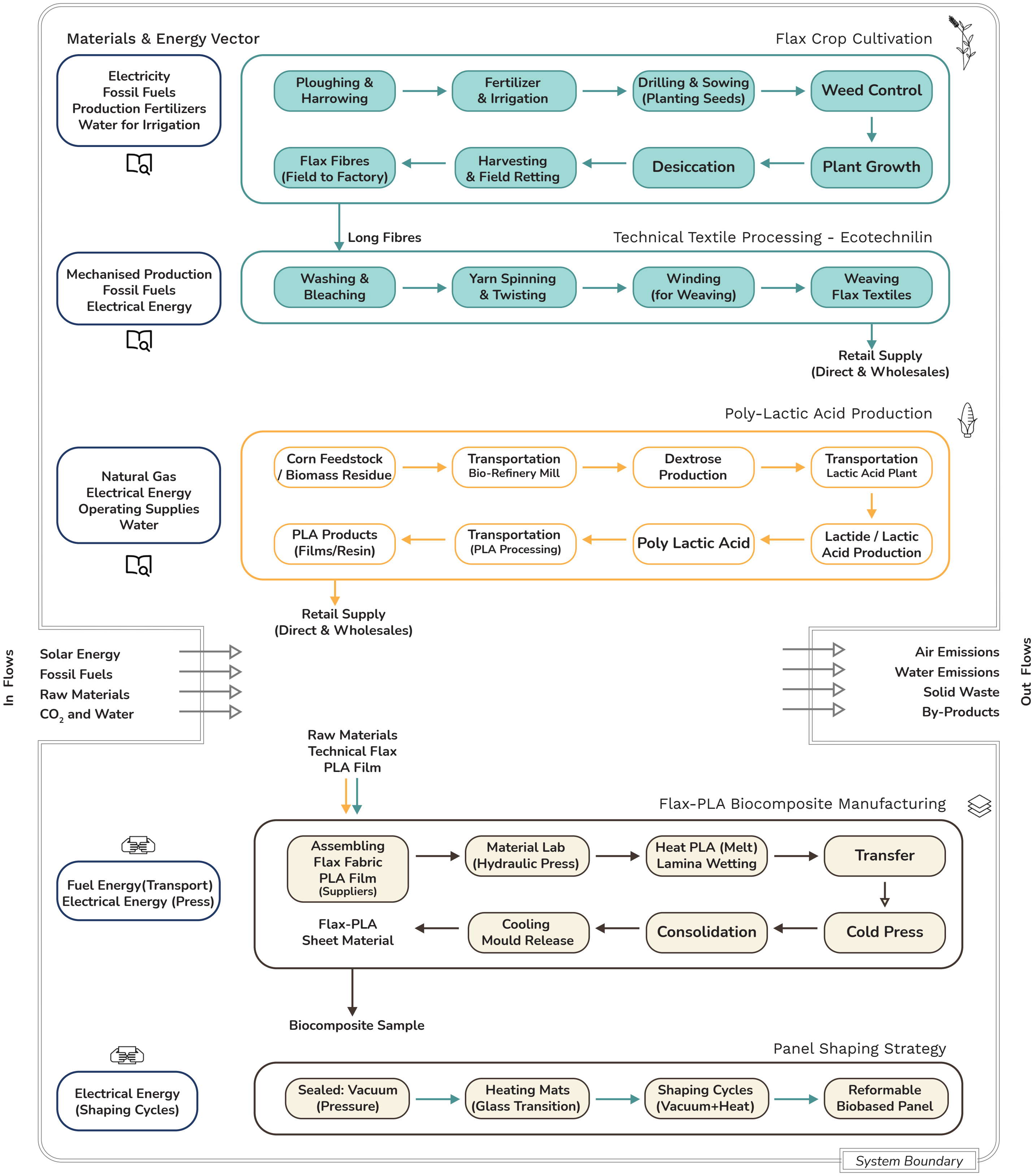
The main interest is the **Global Warming Potential (GWP)**, which is a measure of the product's contribution to climate change. It is an indicator of potential global warming due to emissions of greenhouse gases to the air. Unit used is **[kg CO2-eq]**

6.4

Life Cycle Inventory

Flax & PLA identified process data obtained from Cradle-to-Gate LCA Studies & Literature (Gomez-Campos, 2021; Vink et al., 2003)

Biocomposite manufacturing data obtained from production observations within the scope of this study.



Resource Flow Diagram & Process Tree with System Boundaries for the Flax -PLA Biocomposite Panel Production

6.5

Life Cycle Inventory Assessment

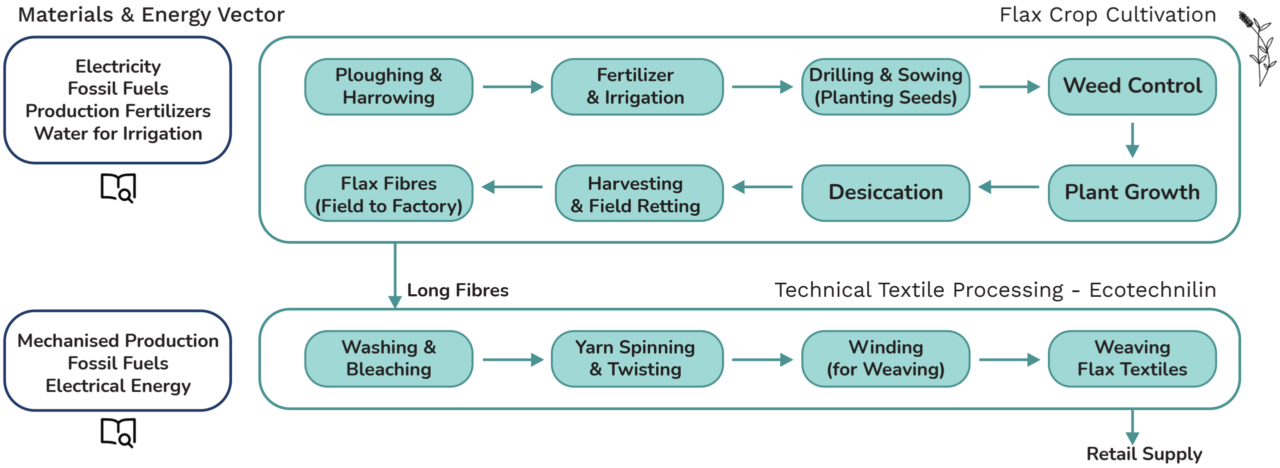
It is the long-term vision to address the consequences of the use of such bio-based composites for the building sector, though the full assessment is beyond the scope of the present study.
Therefore the impact assessment follows a cradle-to-gate approach for the flax fibre production, PLA production data and it will also blend in the manufacturing of the biocomposite production.

CRADLE TO FACTORY GATE - FLAX TEXTILE

(Le Duigo et al., 2011) = **- 1.4 kg CO_2 eq /kg Flax Fibre**
(ANSYS) = + 0.198 **kg CO_2 eq /kg of Flax Textile**

Considering a carbon sequestration figure for the GWP of Flax
Functional Unit = **1 kg of Technical Textile**
Geographical Context = Normandy, France (Ecotechnilin)

The overall GWP impact of the production of 1 m^2 Woven Flax Fabric (grammage of 360 g/m^2)
≈= - 1.4 + 0.198 = **- 1.2 kg CO_2 eq /kg of Flax Textile**



Flax Raw Material Consumption = **- 1.2 kg CO_2 eq /kg of Flax Textile**
ANSYS, Gonsalez-Garcia et al., 2010; Le Duigou et al., 2011

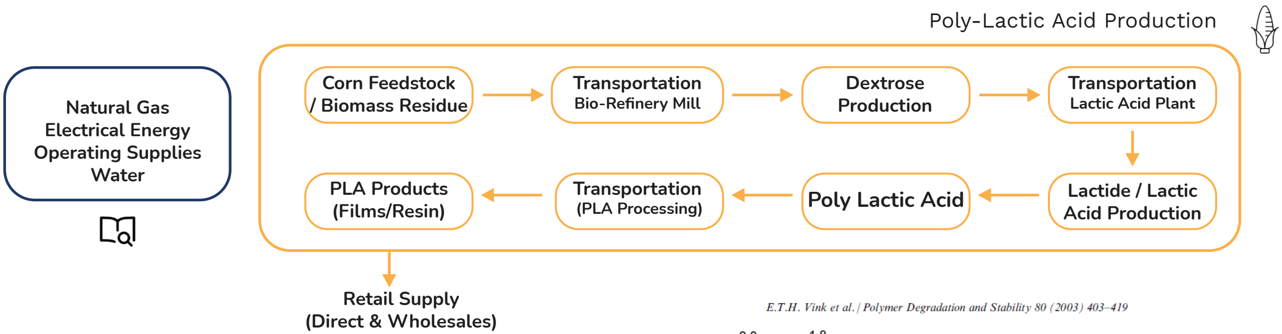
CRADLE TO FACTORY GATE - PLA Film

Considering a carbon sequestration figure for the GWP of PLA
Functional Unit = 1 Kg of PLA

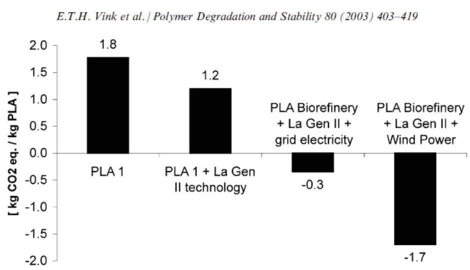
Highly cited study on PLA manufacturing Cargill Dow : NatureWorks (PLA Ingeo)

The overall climate change impact of the production of 1 kg of PLA (density 30-40 um film)

= - 0.3 **kg CO_2 eq /kg of Poly Lactic Acid**



PLA Raw Material Consumption = - 0.3 **kg CO_2 eq /kg of PLA**
(E.T.H. Vink et al., 2003; Le Duigou et al., 2012)



A carbon sequestration figure for the Global Warming Potential (GWP) of flax and PLA, underscoring the importance of responsible forestry and agriculture. It's crucial to note that this assumes the fibres will be regrown to the same production yield, a feasible scenario given sustainable and responsible agricultural practices.

GATE TO GATE - BIOCOMPOSITE PRODUCTION

Functional Unit = **1 m² of Biocomposite**
1 Kg of Biocomposite

Geographical Context =Netherlands, Europe

For 1 m² BioPanel

The overall climate change impact of the production of 1 m² 464 Composite would be
(density = 2.74 kg/m³ ; grammage of 8085.375 g/m²)

Data Obtained (Own Work)
For 1 m² of 464 Panel, as in Design Check
l = 1000 mm , w = 1000 mm , t = 2.95 mm

Weight of Flax Textile (4 Layers)= 4814.00 grams
Weight of PLA Film (88 Layers) = 3271.375 grams

Total Weight of 464 Panel (Post Thermoforming)
= 8.085 kilograms

Raw Material Consumption/ 1 m² Panel
GWP from Flax = - 5.7768 kg of CO_2 equivalent
GWP from PLA = - 0.98 kg of CO_2 equivalent

Biocomposite Consolidation / 1 m² Panel
(15 mins ≈ (Heat 8 mins) +(Press 5 mins) ±2 mins)

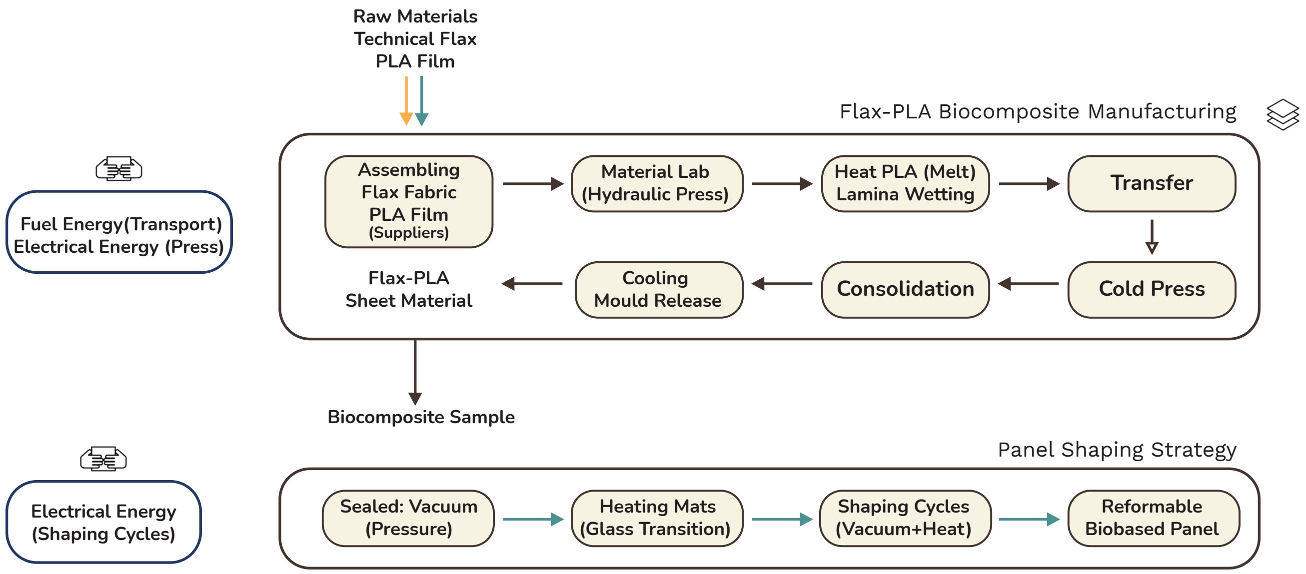
Hydraulic Press GWP = 2.28 kg CO_2 eq
1 kWh = 3.6 MJ
Energy = 3 * 400V * 16A * 0.25h
= 4800 Wh = 4.8 kWh
= 4.8 * 3.6 MJ = 17.28 MJ
Global average carbon intensity for electricity generation (IEA) = 0.132 kg CO_2 eq/MJ

Emissions = 4.8 kWh * 0.132 kg CO_2 eq/MJ
= 2.28 kg CO_2 eq

Transport / 1 m² Panel
Avg CO_2 emissions from Freight = 52.7 g CO2 eq per tonne-kilometer for freight (EEA)
CO2 eq = 30 km * 0.041 kg CO_2-eq/km = 1.581 kg CO_2 eq (Avg Trip between Hydraulic Press & Material Lab)

Shaping Cycle/ 1 m² Panel
Vacuum Pump Time = 10 mins
Energy = Power * Time = 0.15 kW * (10/60) hours = 0.025 kWh = 0.025 * 3.6 MJ = **0.09 MJ**
Emissions = Energy * 0.475 kg CO2 eq/kWh = 0.025 kWh * 0.475 kg CO2 eq/kWh = 0.011875 kg CO2 eq
Heating Mat Time = 10 mins
Power = 48 V * 25 A = 1200 W
Energy = Power * (10/60) hours = 1200 W * (10/60) hours = 200 Wh = 0.2 kWh = = 0.2 * 3.6 MJ = **0.72 MJ**
Emissions = Energy * 0.475 kg CO2 eq/kWh = 0.2 kWh * 0.475 kg CO2 eq/kWh
= 0.095 kg CO2 eq * 0.132 kg CO2 eq/MJ = 0.09504 kg CO2 eq
Total Emissions = 0.011875 kg CO2 eq + 0.095 kg CO2 eq = 0.106875 kg CO2 eq

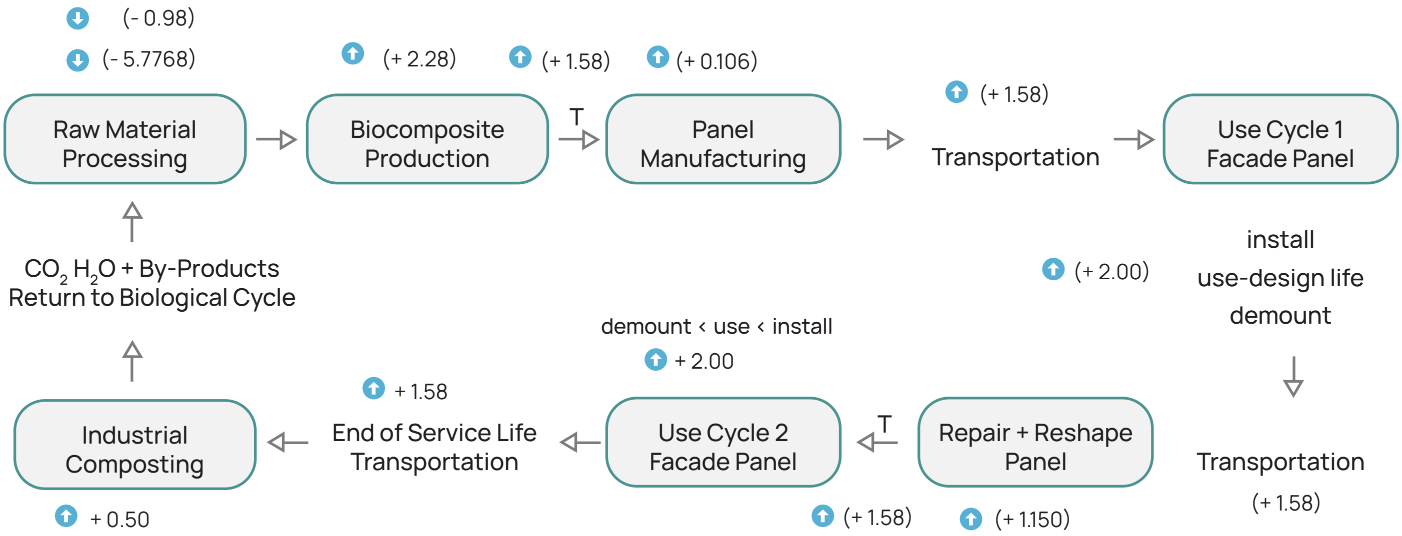
Flax Textile is sourced from Europe, and PLA is sourced from Corn Residue Biomass Stocks, Freight in Europe
Flax + PLA + Consolidation + Shaping Cycle + Transport
= - 5.7768 -0.98 + 2.28 + 0.106 + 1.58 = **-2.7908 kg of CO_2 equivalent/1m² BioPanel**



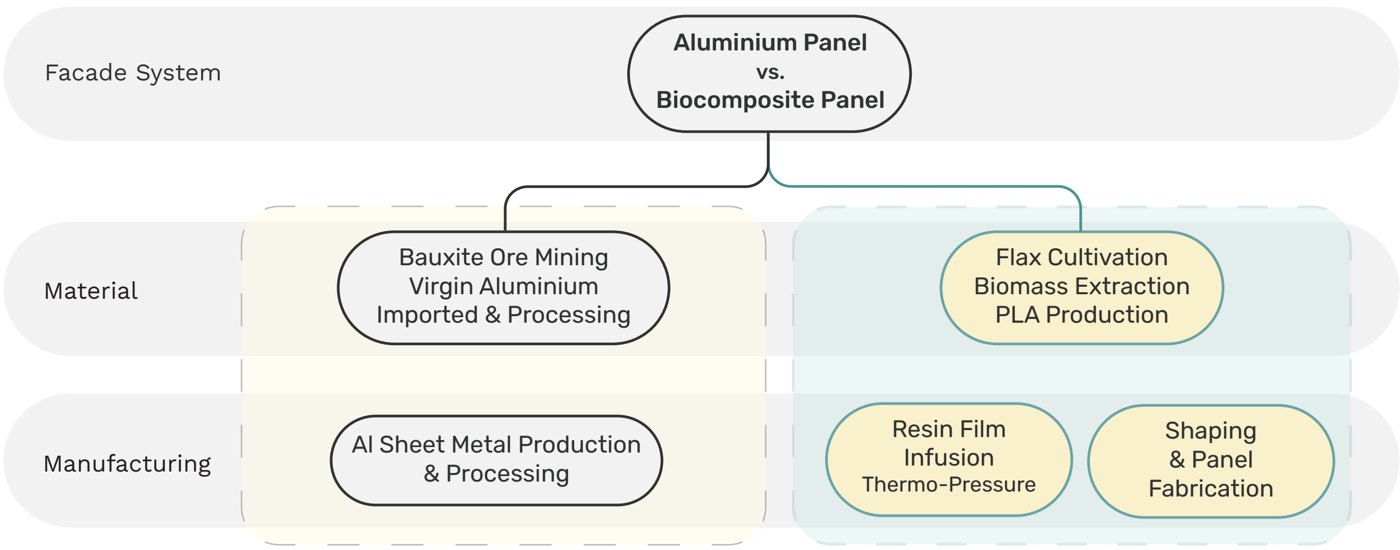
6.6

Life Cycle Impact Assessment

Simplified LCA Flow (Embodied Carbon across Lifecycle) = **+ 9.1792** kg CO_2 eq/m² **of Bio Panel**



Cradle to Gate Comparison: 1m² Anodized Aluminium Sheet (3mm)



79 kg CO_2 eq/m² of Al Sheet

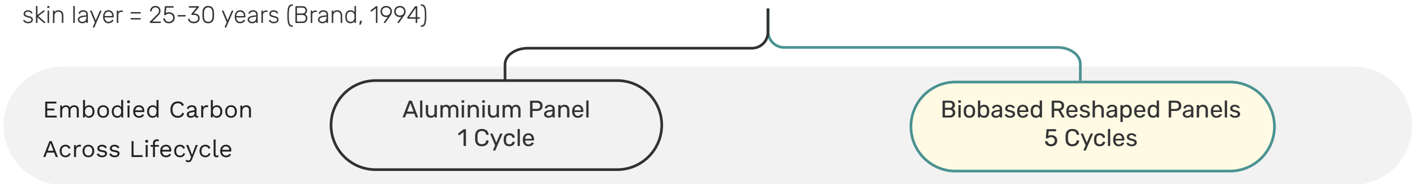
-2.7908 kg CO_2 eq/m² of BioSheet

Gate to Use Comparison: 1m² Anodized Al. Panel (3mm) vs. 1m² Biocomposite Panel (2.95 mm)

Considering the lifespan of a building's skin layer = 25-30 years (Brand, 1994)

Facade Design Life (25 years)

* Omitting operational carbon



+ `79 kg CO_2 eq/m² of Al Sheet + 2.5 kg CO_2 eq (site)
(Density of 3mm Al Sheet = 2.7 g/cm³)

= **+ 81.5** kg CO_2 equivalent

+ 9.1792 kg CO_2 eq *** 5 times**
(Assuming each lifecycle would span for 5 years, one use cycle for 2 .5 years)

= **+ 45,896** kg CO_2 eq

6.7

Comparative Analysis

Evaluation of Embodied Carbon Aluminum Facade in Case Study Panel vis-à-vis Flax PLA Composite as a substitute material

Aluminum, prized for its robustness in facade construction, is becoming increasingly sustainable with better recycling rates, yet the burgeoning global infrastructure demand is likely to rely more on carbon-intensive virgin aluminum.
The fact that 65% of Europe's consumed aluminum is sourced from outside the EU Emissions Trading Scheme adds more embodied carbon due to energy-intensive processes, highlighting the need for environmentally friendly alternatives like bio-composites, particularly in the absence of a comprehensive database detailing the embodied carbon of construction materials

Strength Comparison

A 3 mm thick Aluminum panel has a typical UTS ranging between 100 - 150 MPa.
Comparatively, the Ultimate Tensile Strength (UTS) of **C464 Biocomposite is approximately 100 MPa, while the reshaped material measures around 85 MPa.**
Although the reshaped biocomposite exhibits lower strength parameters than Aluminum, it still surpasses the threshold necessary for a structurally sound facade.

Reflecting on the True Design Life

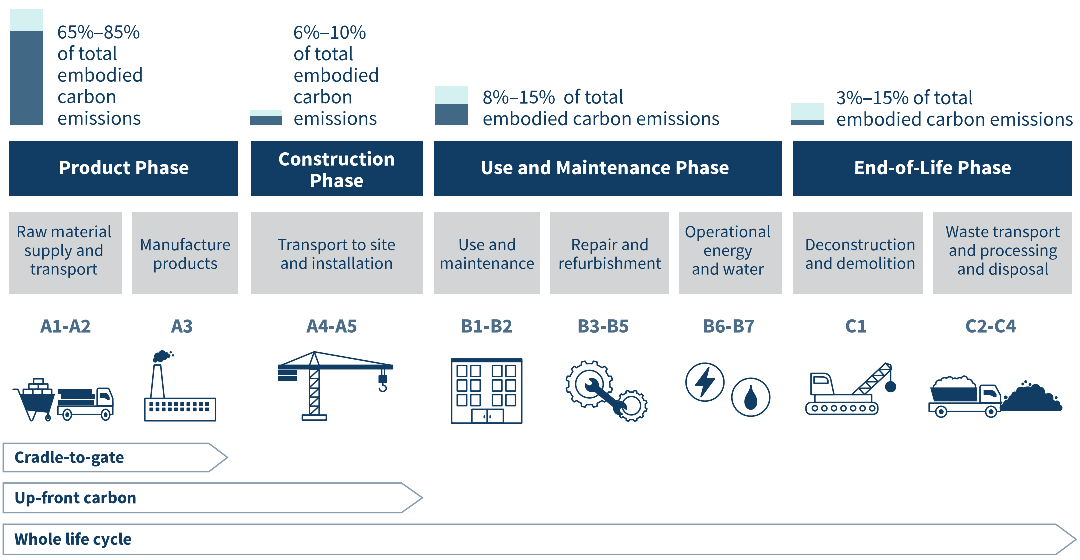
Various research findings regarding the impact of weathering on the strength parameters of bio-composites, particularly Flax with PLA, support that employing a reshaping methodology can enhance the design lifespan of bio-composites if used as facade materials. This improvement in use of biocomposites will make them **highly competitive** in relation to **embodied carbon content** when **compared** to an **aluminum facade.**

This is especially noteworthy given that the typical lifespan of a facade often falls short of the building's intended design life, so the building sector needs to reimagine facade's with materials that age with the facade, and not unnescessary opt for materials like Aluminium that outlive a facade's design life by 50 extra years. However it is worth mentioning that the embodied carbon of the aluminium panel produced from recycled aluminium may be lower.

CRADLE TO GATE Embodied Carbon: Product Phase Lifecycle Stages A1-A3 (kg CO_2e/per m^2)

Regarding the 3 mm thick Aluminum sheet, its embodied carbon stands at (Environmental Product Declarations of Anodized Aluminium Sheets in accordance with ISO 14025 and EN 15804) **+ 79,0 kg CO_2e/ 1 m^2 of Al. Sheet**

Conversely, the C464 biocomposite exhibits a significantly lower figure at (own work documented in this study) **-2.7908 kg CO_2e/ 1 m^2 of BioSheet**



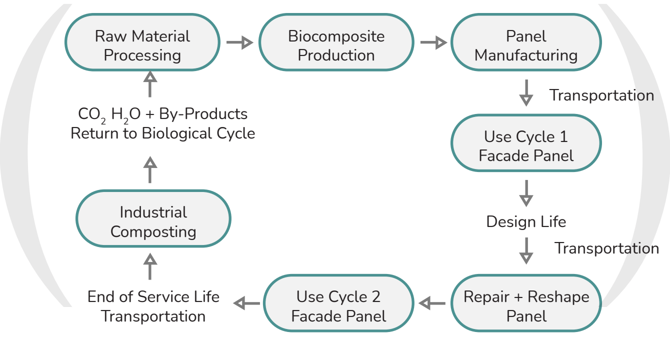
Source: RMI

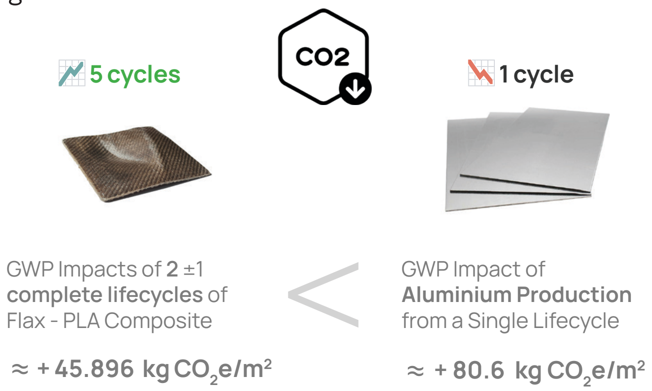
6.8

Interpretations

kg CO_2e/m² for 25 years

WHOLE LIFECYCLE CARBON: Product Phase Lifecycle Stages A1-C4





≈ + 9.1792 kg CO_2e/m² for 1 Lifecycle of 5 Years (Use life = 2.5 Y)

Undeniably, Flax-PLA biocomposite may require more frequent replacement due to degradation in mechanical properties from weathering impacts, compared to the durability of Aluminum.

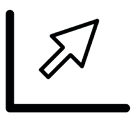
Conservative Estimates

Drawing upon existing literature (Le Duigou et al., 2009; Sit et al., 2022), the lifecycle of flax-PLA biocomposite material in this study is currently calculated to sustain a 2.5-year use cycle (first design life) and 5 years for a complete lifecycle.

It's worth mentioning that this 2.5 years figure represents a deliberately conservative estimate; owing to the infancy of this research and material and the substantial scope for prolonging its lifespan through continued research and innovation.

By **setting the bar low** for this comparison with Aluminum's lifecycle, we create a baseline for potential carbon savings.
The understatement shows the tremendous opportunity for additional CO_2 savings that even modest enhancements in the biocomposite's lifespan can unlock, making the future research for flax-PLA biocomposites more compelling.

Gauging Advancement without Carbon Footprint Escalation



Hence, the path to extending the lifespan of the biocomposite is lined with a critical condition: the material's carbon footprint should not typically significantly rise as a result of lifespan enhancement. Hence, the challenge lies in advancing the biocomposite's first design life to last for 5 or even 10 years without surpassing the carbon impact of its 2.5-year counterpart.

EMBODIED CARBON (ACROSS LIFECYCLE) FOR 25 YEARS

+ `79 kg CO_2 eq/m² of Al Sheet + 2.5 kg CO_2 eq (site)
(Density of 3mm Al Sheet = 2.7 g/cm³)

= + **81.5** kg CO_2 equivalent

+ **9.1792** kg CO_2 eq * **5 times**
(Assuming each lifecycle would span for 5 years, one use cycle for 2 .5 years)

= + **45,896** kg CO_2 eq

Life Cycle Repetitions

It is vital to recognize that even the most conservative assumption of a short lived **biocomposite's** cumulative environmental impact over the typical lifespan of a facade skin (approximately 25 years) **remains significantly lower than aluminium's, even when multiple replacements are factored in.** This signifies its potential as a more sustainable choice.

6.9.1

Research Conclusion

This study has yielded several novel findings of importance to the scientific community. The following section aligns these insights with the initial research questions, thereby providing a summary of the research journey.

Main Research Question was formulated as:

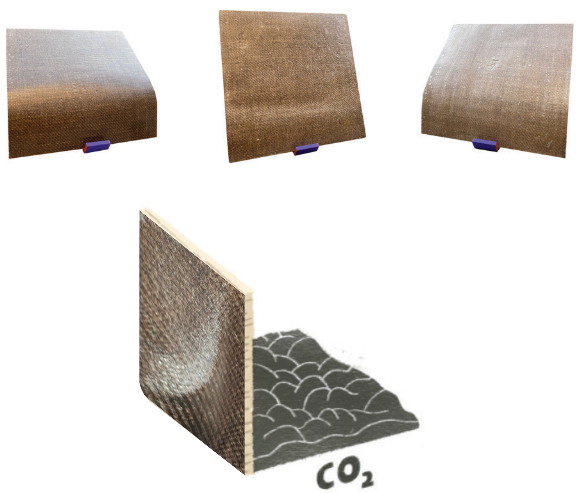
How to engineer a fibre-reinforced biocomposite cladding panel for complex geometric facades?

This research ventured to engineer a fibre-reinforced biocomposite, integrating material science & structural design knowledge and positioning it with facade engineering as a cladding material. The journey began with identifying suitable constituents, as the vast literature guided this study towards Flax fibres and PLA and their optimum pairing. However, this combination had to qualify with the rigorous structural demands of a facade application while innovating on sheet material properties.

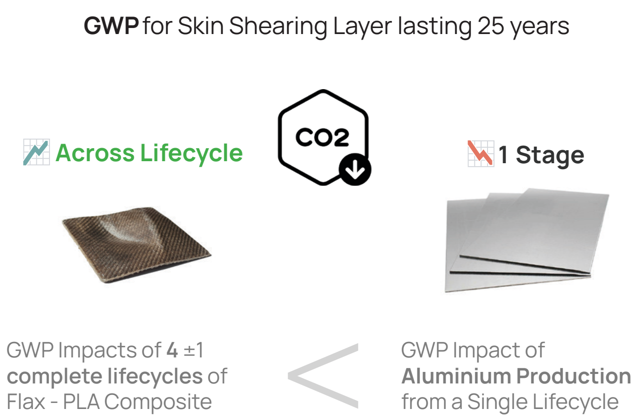
The unique challenge lay in the need for this biocomposite to adapt to complex geometric facades, focusing on case studies typically realized through economically viable, developable sheet materials like aluminium. Our research identified the gap in the use of biocomposites. It proposed the possibility of a 100% biobased high-pressured laminate material – a flax-PLA biocomposite – that could function as a developable sheet. We explored its reshaping potential while maintaining its integrity, pushing the boundaries of circularity in biocomposites.

Crucially, we discovered our biocomposite's consequent properties in the context of cladding systems; also that it retained its original strength and durability even after being subjected to a novel strategy based on vacuum+thermoforming principles, experimentally validating their ease of developability as an economical sheet material. Upon estimating biocomposites' potential lifecycle as a facade component & comparing the environmental impact of our biocomposite panels to traditional aluminium panels with an LCIA, the findings were promising, as they presented significantly lower overall implications for the flax-PLA biocomposite, even considering its current shorter service life and the necessity for multiple life cycles to meet a facade's design life.

In conclusion, the endeavour to engineer a fibre-reinforced biocomposite for complex geometries has successfully demonstrated the feasibility of Flax-PLA composites as a circular and biobased alternative to conventional panels like aluminium. Forming and reshaping these panels into flat sheets without distortion allows reusability and repurposing, effectively retaining their embodied energy across multiple life cycles. Future work on extending the lifespan of biocomposites could further enhance their environmental advantage and industrial acceptance in the AEC sector.



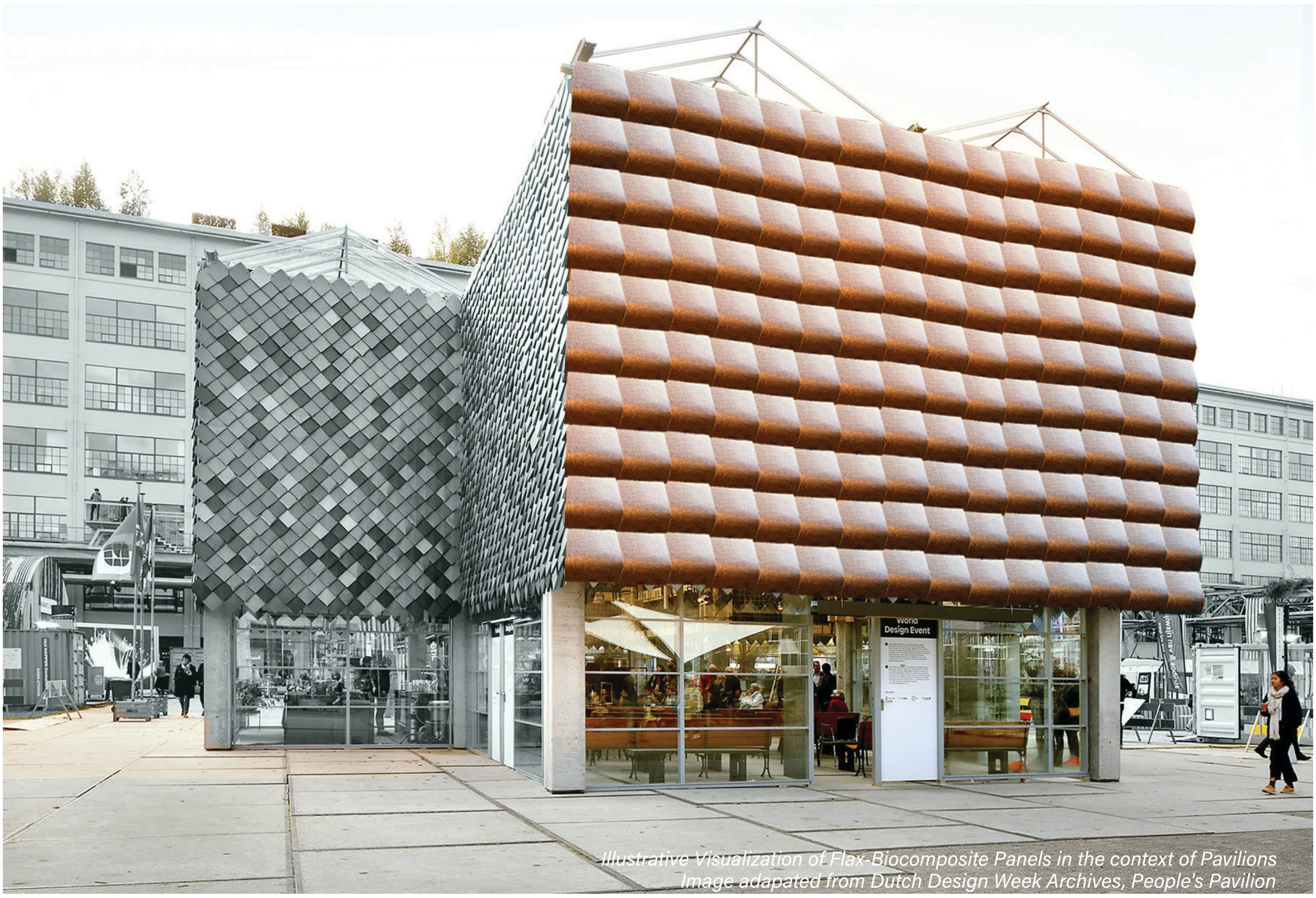
-2.7908 kg CO_2e/ 1 m^2 of BioComposite



6.9.2

Visualizations

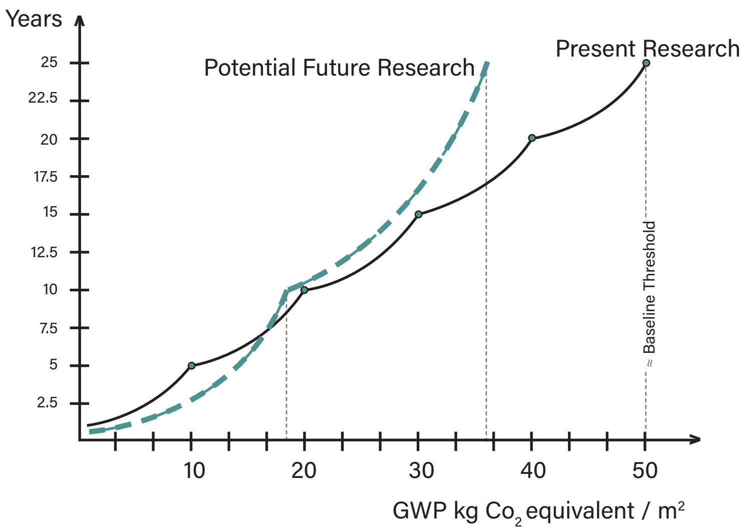
Illustrative Visualization of Flax-Biocomposite Panels in the context of Pavilions
Image adapated from Dutch Design Week Archives, Growing Pavilion



Illustrative Visualization of Flax-Biocomposite Panels in the context of Pavilions
Image adapated from Dutch Design Week Archives, People's Pavilion

6.10

Future Work



Recommendation

When evaluating the CO2 impact over a facade's expected lifespan of 25-30 years, the lifecycle repetitions for each material become crucial.

A biocomposite with a 5-year span/lifecycle would necessitate 5-6 cycles to account for the whole design life while a 10-year span/life cycle biocomposite would require just 2-3 cycles, hence reducing the processing & operational carbon footprint.

Gauging Future Paths

According to the current literature, any reasonable technological process to enhance the lifespan, will not typically overshoot the baseline conservatively calculated. As the process, might increase the embodied carbon along with the service life, the number of cycles required for facade life would be lesser than the threshold.

Present Research
Conservative Baseline

1 Lifecycle of 5 Years	**≈ + 10**	**kg CO_2eq/m²**
25 Year - 5 Loops	≈ 5x10	kg CO_2eq/m²
	≈ 50	**kg CO_2eq/m²**

Future Research with an Advancement
Say,

1 Lifecycle of 10 Years	**≈ + 18**	**kg CO_2eq/m²**
25 Years ≈ 2 Loops	≈ 2x18	kg CO_2eq/m²
	≈ 36	**kg CO_2eq/m²**

While this research has advanced our understanding of fibre-reinforced biocomposites as a potential facade material due to the proven concept of developability, there remain crucial areas that warrant further exploration.

Extended **Research Refinement**

Within the scope of this research, several themes arose, which can be of immense scientific relevance if investigated as immediate next steps. To sum up the aspects of this research that can be extended and refined further are:

- **Design & Functional Exploration**
- **Durability & Field Tests**
- **Extension of Lifespan & LCA Post Advancement**
- **System Assembly & Installation Framework**

Challenges & **Limitations**

Material Consistency
Ensuring consistent quality and characteristics across batches of biocomposites can be a challenge due to natural variations in bio-based raw materials.

Durability Assessment
Understanding the long-term durability of iocomposites when exposed to different environmental conditions over time, can vary across climates and contexts.

Regulatory Hurdles
Biocomposites, being relatively novel materials, may face regulatory hurdles, especially regarding building codes and safety regulations, specially for high-rise structures. It is best to aim for widespread low-rise applications for immediate applicability.

Industry Acceptance
There can be resistance from AEC industry due to unfamiliarity with biocomposites, their perceived performance, and longevity compared to traditional materials, however, collaboration with industrial research labs can close the commercial gap.

Production Line Framework
Developing cost-effective and scalable manufacturing lines that maintain the integrity of the biocomposites while allowing for complex shapes and geometries will need to be adapted with a framework.

6.11

Way Forward

Future Themes of Research

Future research must delve deeper into the performance metrics of facade materials, specifically Flax-PLA composites, to validate their integration into the construction sector.

This involves experimental and analytical evaluations to ensure these composites meet the requirements for facade applications.

The typology of the facade also affects the material's carbon footprint, which in turn influences design decisions. For instance, a temporary structure might have a different carbon footprint than a residential one.

Ongoing exploration in this field will facilitate the optimization of bio-composites for facade usage.

This will usher us towards a more sustainable approach to facade design, harmonizing functionality, aesthetics, and ecological responsibility.

Facade Performance Checklist

During the case study, Scheldebouw B.V, Netherlands shared a Facade Performance Checklist, that is the protocol document of the organization. Such a list, is not available to the research and development sectors, as it stems from industrial standards and regulations. However, the Scheldebouw facade performance checklist has the power to serve as a significant tool that bridges the gap between the research sector and the industry. It is this checklist that contractors like Scheldebouw refer to while they internally cross check with facade manufacturers and suppliers of part, products and materials of unitized facades. It provides a comprehensive set of parameters that any potential facade material, including Flax-PLA composites, should meet.

Understanding this checklist can offer significant insights for future research, as it provides a framework outlining what the industry values and requires. Therefore, Flax-PLA composites need to be developed hierarchically, in line with these parameters. Research should ensure the composite ticks off each criterion on the checklist, thus ensuring its readiness for future integration into the facade design process.

Major Research Themes

Minor Research Themes

Fire Performance
Flame Propagation & Smoke Production
Combustibility & Material Reaction

Weather Tightness
Air & Water Infiltration
Air & Water Exfiltration
Light Transmittance & Reflectance

Design Details
Application Exploration
Facade Archetypes

Durability & Lifetime Expectancy
Accelerated Ageing
Durability of Material
Repair & Replacement of Material

Implementation
Production Methodology & Tolerances
Installation Methodology (Assembly)

Material Performance
Thermal Line, Thermal Behavior
Impact Test
Fixing Test

Safety & Security
Burglary Resistance Integration
Blast & Ballistic Resistance

Movement & Tolerances
Installation Tolerances
Building Movement Tolerances

Acoustical Behaviour
External Noise Transfer
Internal Noise Reduction (Flanking)

Scheldebouw BV

PERMASTEELISA GROUP

FAÇADE PERFORMANCE CHECKLIST - Part B

- **Project number** : **nnnnnnnnnn**
- **Project** : **nnnnnnnnnn**
- External Wall Type : nnnnnnnnnn

Contract specification:	**A**	: Report, number,	Rev..; Date..		
	B	: Report, number,	Rev..; Date..		no
	C	: Report, number,	Rev..; Date..		ch
					na
Other:		Report, number,	Rev..; Date..		ip

ITEMS:		Report Reference:	Performance Criteria:	Scheldebouw Criteria:	
		Specification of performance criteria			
B1	**Movements & Tolerances**				
B1.1	**Building structure**				
B1.1.1	**Influencing bracket**				
	• Structural tolerances				
	• Cast-in channel tolerances				
	• Dead load deflection slab edge (without cladding panels)				
	• Dead load deflection slab edge (with cladding panels)				
B1.1.2	**Influencing joint**				
	• Column shortening				
	• Differential deflection of slab edge after installation (lifetime building)				
	• Extra live load deflection slab edge (due to additional finishes)				
	• Shrinkage				
	• Differential settlement				
	• Sway movement				
	• Interstory drift due to seismic event				
	• Thermal movement				
	• Creep				
B1.2	**Cladding**				
	• Assembly tolerances				
	• Installation tolerances				
B1.3	**Summary of Movements & Tolerances**				
•	Required horizontal and vertical adjustment of the façade bracket				
•	Required vertical movement joint between panels				
•	Required horizontal movement joint between panels				
B2	**Structural behaviour**				
B2.1	**Load assumptions for structural calculations**				
	• Dead load				
	• Wind load				
	• Snow load				
	• Impact loads				
	• Barrier imposed loads				
	• Cleaning cradle (impact) loads				
	• Window wash restraint loads				

B2.2 Deflection limits of cladding members

B2.2.1 Framing members
- Framing members supporting dead
- Framing members supporting wind

B2.2.2 Glass
- Single glass units
- Double glass units
- Triple glass units

B3 Environmental Behaviour
- U-value
- U-value spandrel
- U-value frame
- U-value glass
- Condensation risk assessment
- Solar performance
- Light Transmittance
- Reflectance

B4 Acoustical Behaviour
- External sound reduction
- Internal sound reduction (horizontal flanking)
- Internal sound reduction (vertical flanking)
- Whistling sounds

B5 Weather Tightness

B5.1 Air tightness infiltration
- Specification (Pa)
- Performance requirements / classification
- Performance requirements / classification of doors and windows

B5.2 Air tightness exfiltration
- Specification (Pa)
- Performance requirements / classification
- Performance requirements / classification of doors and windows

B5.3 Water tightness
- Specification Static (Pa)
- Specification Dynamic (Pa)
- Performance requirements / classification
- Performance requirements / classification of doors and windows

Figure: Facade Performance Checklist

Source: Scheldebouw BV, Permasteelisa Group

B6 Fire Performance
- Combustibility
- Smoke
- Surface spread of flames
- Toxic reaction
- Fire resistance of the façade (R,E,I,W, i→o / o→i)
- Fire and smoke stopping

B7 Safety & Security

B7.1 General
- Glass classification

B7.2 Burglary resistance

Glass classification
- Frame classification
- Iron mongery classification

B8 Durability & Lifetime Expectancy
- Durability of primary components
- Durability of secondary components
- Replacement of components
- Requirements of structural sealant

B9 Performance Testing
- Weather tightness test
- Rainwater ingress test
- External sound reduction test
- Internal sound reduction (flanking) test
- Impact test
- Fire test
- Bomb blast
- Burglary test
- Ballistic test
- Fixing test
- Site host test

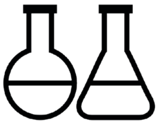
Mock-up's

6. 12 . 1

Scientific Reflections

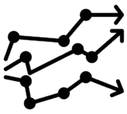
TECHNICAL REFLECTION

Exploring Other Bioplastics



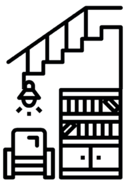
In retrospect, the exploration of other bioplastics as matrices could have further enriched this research. These alternatives could potentially toughen and improve the material composite and properties of the Flax-PLA composite. Literature indicates that attempts to explore these alternatives have shown promise. This could be a potential avenue for future research, expanding the scope of biocomposites in facade engineering.

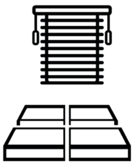
Refining the Testing Order



While the current testing program provided valuable insights, an extended timeline could have incorporating an examination of the effects of weathering and water absorption between the first and second shaping cycles. Doing so, would have connected all the results in a single data set, prior to the mechanical studies. Although our current approach yielded robust results, this additional step of weathering / accelerated ageing before mechanical tests could have accurately simulated the proposed strategy and refined our projections, adding an indisputable dimension to the research outcomes

Functional Reflection





Beyond facade applications, the Flax-PLA composite's robustness and sustainability make it suitable for various uses within the building sector. It could serve as an eco-friendly material for interior partitions, ceiling and wall panels, and even furniture like tables, chairs, and shelves. Additionally, it could be utilized in ancillary structures such as staircase railing systems and temporary structures, like pavilions. This composite's potential extends throughout the building sector, suggesting a multitude of future applications.

AESTHETICAL REFLECTION

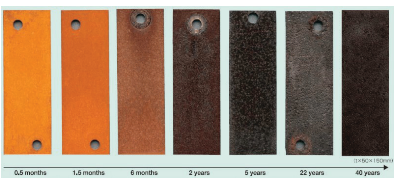
Variants

Dyed Flax Fibres

The Flax-PLA composite, with its natural and technical fabric, offers a unique aesthetic appeal. The technical linen fibres hold the potential to be dyed with any desired colour, using natural or food dyes, thus maintaining the biobased composition while adding a touch of personalisation.

As the aesthetic of this biobased material differs from that of metal, it aligns closely with timber or wood-reinforced polymers, which are often chosen for their natural aesthetics and their ability to age gracefully with the building facade.

Ageing of Corten Steel



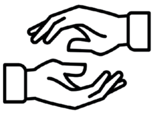
This opens up an intriguing possibility: observing how biobased panels age alongside the structure they are part of, and comparing user preferences for ageing steel, timber, and biocomposites. Each material, with its unique ageing process, will likely find its own niche in the architectural world, offering a range of aesthetic choices for future buildings.

6. 12 . 2

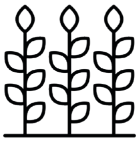
Societal Reflections

CONTEXTUAL REFLECTION

Transferable Skill, Material & Method



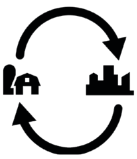
The Flax-PLA biocomposite stands out for its unique adaptability to varying levels of technological development. The low-tech and scalable strategy explored in this research can be implemented without the need for expensive infrastructure and machinery, making it accessible and adaptable across different contexts & socio-economic backgrounds.



Depending on the climate and available resources of a region, the fibres used could shift, reflecting the local context. For instance, in India, Jute could be the fibre of choice, while in Asia, Kenaf might be more suitable. This adaptability not only enhances the sustainability of the biocomposite but also allows for a level of local customization that is rare in building materials. This unique feature of the Flax-PLA biocomposite could pave the way for truly context-sensitive, sustainable architecture.

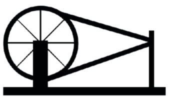
SOCIO-CULTURAL REFLECTION

Urban Rural Flows



At a local level, the production of biocomposites can stimulate local economies, particularly in developing countries. By sourcing natural fibres and biomass locally, the production process can support local agriculture and contribute to rural development. This can be particularly impactful in regions where agriculture is a primary sector of the economy.

Low-Tech Knowledge



The composition adaptability of the biocomposite to use different fibres allows for cultural relevance and diversity. Depending on the local context, different natural fibres or biomass sources along with local methods, resources, and knowledge. This contributes to the preservation and valorization of local cultures and practices.

Developing Regions & Economies

The Flax-PLA biocomposite represents a significant opportunity for developed economies, particularly those in the global north. As the developed nations strive to lower their environmental impact, the adoption and investment in sustainable, biobased materials like this composite become increasingly crucial.

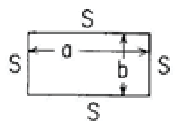
The production and use of biocomposites can stimulate economy & employment in sectors like construction, manufacturing, and agriculture, leading the way in the global inclusivity towards sustainable development. It closely aligns with the growing consumer demand for environmentally responsible products, enhancing competitiveness in the global market.

Appendix

Roark Table

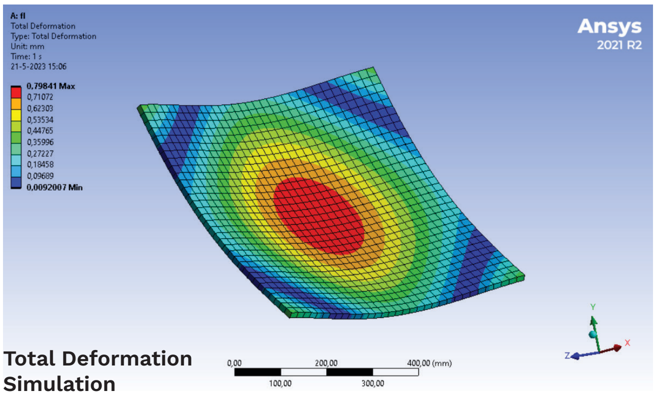
TABLE 11.4 Formulas for flat plates with straight boundaries and constant thickness

NOTATION: The notation for Table 11.2 applies with the following modifications: a and b refer to plate dimensions, and when used as subscripts fo parallel to the sides a and b, respectively. σ is a bending stress which is positive when tensile on the bottom and compressive on the top if loading reaction force per unit length normal to the plate surface exerted by the boundary support on the edge of the plate. r'_o is the equivalent radius of cont and is given by $r'_o = \sqrt{1.6r_o^2 + t^2} - 0.675t$ if $r_o < 0.5t$ and $r'_o = r_o$ if $r_o \geqslant 0.5t$

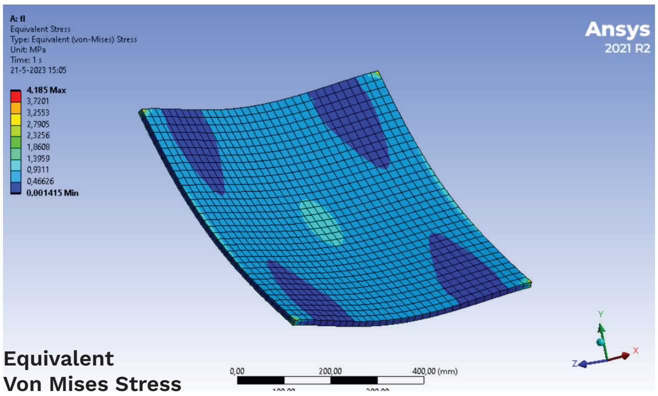
Case no., shape, and supports	Case no., loading	Formulas and tabulated specific values
1. Rectangular plate; all edges simply supported 	1a. Uniform over entire plate	(At center) $\sigma_{max} = \sigma_b = \dfrac{\beta q b^2}{t^2}$ and $y_{max} = \dfrac{-\alpha q b^4}{Et^3}$ (At center of long sides) $R_{max} = \gamma q b$

a/b	1.0	1.2	1.4	1.6	1.8	2.0	3.0	4.0	5
β	0.2874	0.3762	0.4530	0.5172	0.5688	0.6102	0.7134	0.7410	0.7
α	0.0444	0.0616	0.0770	0.0906	0.1017	0.1110	0.1335	0.1400	0.1
γ	0.420	0.455	0.478	0.491	0.499	0.503	0.505	0.502	0.5

Role of FEA: The experimental test data (literature) is input into FEA simulations
These simulations will help refine the design and manufacturing process.



Total Deformation Simulation



Equivalent Von Mises Stress

Calculation for GWP/kg of Aluminium 3mm sheet

The average density of aluminum is approximately 2,700 kg/m³.
To calculate the weight of a 3 mm thick 1 m² anodized aluminum sheet, we need to determine:

Volume = Thickness * Area = 0.003 m * 1 m² = 0.003 m³
Weight = Volume * Density = 0.003 m³ * 2,700 kg/m³ = 8.1 kg

For illustrative purposes, let's consider a general figures by the World Aluminium Association, 2018
Global average carbon intensity for primary (virgin grade) aluminium production
= 11.8 tonnes CO_2-eq/tonne aluminium
= 11.8 kg CO_2-eq/kg aluminium

This includes both direct greenhouse gas emissions from aluminium production and indirect emissions from electricity use. Multiplying the mass of Panel by the CO_2 equivalent per kg value:

CO_2 eq = mass * CO_2 eq per kg = 8.1 kg * 11.8 kg CO_2-eq/kg = 95.58 kg CO_2 eq / Kg Aluminium

6. 12

Reflection Questions

Question 1

“What is the relation between your graduation project topic, your master’s track (Ar, Ur, BT, LA, MBE), and your master’s programme (MSc AUBS)?”

My graduation project, “Circular Cladding Design”, forms a direct and intrinsic link with my master’s track, “Building Technology” (BT), and my master’s programme, “Master of Science Architecture, Urbanism and Building Sciences” (MSc, AUBS).

This project topic is a quest for a 100% biobased and circular cladding solution with a lower environmental impact and global warming potential than conventional facade materials.

Developing an alternative & competent material can lessen the construction industry’s impact on global emissions and be a small step in mitigating climate change, thus aligning with the principles of Sustainable Building Technology.

This project examines the implications of using biocomposite material as a cladding component and proposes the structural reuse of biocomposites.

Therefore, the study empirically investigates the evolution of the strength and durability parameters upon reshaping the biocomposite for reuse with biodegradable biocomposites.

The intent is to understand how this innovative approach of using reshaped biocomposite components enhances the circularity and lifecycle of the facade cladding.

Furthermore, the project compares this biocomposite material with conventional aluminium in a real-world cladding scenario, contextualising its place in the materials pyramid and giving a deeper understanding of its potential use in the building sector.

The novelty of this research lies in its exploration of a circular cladding design that incorporates a reshaping option with biodegradable biocomposites.

This innovation hints at the future trajectory of circular building materials and has a significant bearing in addressing the pressing challenges of sustainability & circularity in the built environment.

Question 2

“How did your research influence your design/recommendations, and how did the design/ recommendations influence your research?”

The novelty of my research topic was the feasibility check of reshaping strategy as a means to enhance the circular potential & extend the lifespan of the fully biobased & biodegradable material as a building component. Furthermore, this research simultaneously paved the way to explore the diverse potential of repurposing the biocomposite in other areas, such as interior environments.

Specific strength parameters assessed during the testing programs before and after reshaping the materials were found to be fully aligned with the core objective of the research. Consequently, these findings didn’t necessitate or warrant any deviation/ change from the initial hypothesis that steered the research and experimentation phase.

The scope of research was strategically defined to align with the time frame available for the thesis. However, the positive outcome of this project is expected to lead to tangible recommendations for further research, especially the evaluation of the weathering resistance upon first use, fireproofing, acoustical and vibration mitigation characteristics etc., before making the final recommendation or conclusion for broad-based building industry use.

Given that the use of fully biobased & biodegradable materials as building components like cladding is quite futuristic in nature and not fully integrated into current standard building components like cladding, the value propositions offered by this research topic are expected to have international relevance and impact.

The ongoing research for circular building materials is rather pivotal in achieving sustainable development goals pertaining to climate action and responsible consumption and production.

Question 3

“How do you assess the value of your way of working (your approach, your used methods, used methodology)?”

Guided by my dedicated mentors and professors, my research journey – from the initial development stages (pre-experiment) to the current post-experiment period – has been enriching. I greatly attribute my positive experience to my mentors’ and professors’ consistent guidance and encouragement.

I extend my heartfelt gratitude to Professor Olga Ioannaou for introducing me to valuable industry partners and resources who played an instrumental role in shaping this research’s methodology.

My incredible mentors, Prof. Dr Mauro Overend & Prof. Dr Olga Ioannaou, helped craft this thesis with immense sensitivity to my working methods. Research can be an alienating process, but my thought & process was of utmost value to both my mentors, and this always motivated me to keep going despite hiccups through each phase of this journey.

The takeaways I had to extend beyond this thesis, but insight garnered from my professors, starting from:

- the literature review to identify research gaps
- garnering industrial interest in this research,
- to design the experimental program,
- manufacturing samples for testing and validation,
- eventually devising the strategy and prototype helped this thesis come to fruition.

In each step, a multifaceted research methodology resulting from the collective effort of mentors, professors, and resources at TU Delft provided an invaluable learning opportunity.

The expertise extended by our industry partners - Scheldebouw, Janneke Verkerk and Hans Jansen from Permasteelisa Scheldebouw Heerlen and Middelburg - was invaluable. They provided comprehensive, state-of-the-art insights into façade performance, material selection, and industry best practices. In addition, their contributions deepened my understanding of the role of façade contractors in the Netherlands and the UK regarding façade design and circularity.

Finally, I cannot overstate the value of the support I received from Willem Bottger at NPSP. His expertise and assistance while manufacturing samples were pivotal to this research. His contributions went beyond mere guidance; he provided hands-on help using their lab equipment, which greatly enriched the material development aspect of my project. I am profoundly grateful for his involvement in my research journey.

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Question 4

“How do you assess your graduation project’s academic and societal value, scope and implication, including ethical aspects?”

Ethical Aspect

In the face of the mounting challenge of climate change, as a global citizens, it is crucial to our moral responsibility to recognise our collective ethics, to act decisively and adopt sustainable methods in all areas irrespective of religion, culture, location or means of life.

My graduation project holds significant relevance in this regard. It helped lay the mental groundwork for my professional journey & ethics in the built environment. It offered a platform from which I could contribute to my capacity in a small, albeit meaningful & definite way.

Academic Aspect

The integration of fully biobased materials into cladding is still an emerging field. Yet, the concept of reshaping as a methodology to extend the design life of biocomposites, thereby enhancing the overall circularity index, shows significant promise.

Furthermore, utilising entirely bio-sourced and biodegradable composites, such as PLA (matrix), flax (reinforcement), and circular strategies to retain value & integrity is extremely promising.

This theme has potential for further research, particularly when assessing the implication on architectural, structural and constructability parameters.

Societal Aspect

The urgency to target GHG emissions from the building industry makes sustainable initiatives a high priority in contemporary society.

Thus, there lies the immense potential to expand this work on a larger platform with better resources, aligning with society’s increasing receptiveness and encouragement to use circular & biobased alternatives as a building material across segments.

While these materials are already being used in automotive and other industries, introducing this material as a building component will have a much broader impact.

Question 5

“How do you assess the value of the transferability of your project results?”

The innovative approach of reshaping or reconfiguring (reversing) bio-composite materials offers significant potential for prolonging the design life of fully biodegradable bio-composites in diverse forms and applications.

This strategy can be applied and tested for various other bio-sourced and biobased materials.

My assessment of the limiting range of reduction in strength parameters conveys a preliminary yet crucial step in exploring the feasibility of reshaping biomaterials to continue using the same original product in other possible formats.

Conducting further extensive research on the effects of weathering and ageing on the composite’s outer exposed surface and its subsequent impact on strength parameters will strengthen present findings, that reshaping the biocomposite material is one of the promising options to enhance the circularity index of the biocomposite material for use as a cladding component.

What challenges did you encounter during the implementation of the process of developing and reshaping bio-composites, and how did you overcome them?

I had to redo the mould set up many times, till I got it to work as desired. The vacuum pressure was strong, and the pressure kept breaking the weak mould. However, it was all repairable and could be used almost 15-20 times. The assembly I have designed has the opportunity to be a very scaleable setup.

In the process, there were hurdles of composites shifting, and the seal loosening, and other practical issues with reusing the set up over time, however, this was easily tackled with repair and regular maintenance of seals before shaping cycles. I can imagine, how industrially this process could be optimised for larger material panels, and would be positioned in a more effective way inside the mould. However, within the scope of this research project, the scale of the setup worked well, but would need to be scaled up for commercial use case.

07

citations/references appendix

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