



Multi-level Circular  
Process Chain for Carbon  
and Glass Fibre Composites

**MC4 101057394**

Multi-level Circular Process Chain  
for Carbon and Glass Fibre  
Composites

**Deliverable D8.5: Documentation of training materials**

Due date of deliverable: 2025-03-31  
Actual submission date: 2025-03-05

Start date of project: 1<sup>st</sup> April 2022

Duration: 36 months

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Revision 1

Lead Beneficiary: LAB23  
Contributions by: MANAGING COMPOSITES, TECHTERA

Project co-funded by the European Commission within Horizon Europe Framework Programme		
Dissemination Level		
<b>PU</b>	Public	X
<b>SEN</b>	Sensitive information	

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- A. EDUCATIONAL MATERIAL FOR DESIGN ENGINEERS: DESIGN METHODOLOGY (MANAGING COMPOSITES)
- B. EDUCATIONAL MATERIAL FOR PROCESS AND PRODUCT ENGINEERS: CAE METHODOLOGY (MANAGING COMPOSITES)
- C. EDUCATIONAL MATERIAL FOR CIRCULARITY: USING RECYCLED GFRC IN PRODUCT DESIGN AND MANUFACTURING (LAB23)

## 1. INTRODUCTION & OBJECTIVES

Europe's competitive position in carbon and glass fibre manufacturing is relatively weak. Currently, 80% of these fibres are produced outside Europe, and around half of the remaining 20% is manufactured under foreign licences, leading to significant reliance on external sources. The MC4 project offers a valuable opportunity to innovate and safeguard manufacturing processes using recycled materials. This initiative aims to enhance the competitiveness of European companies in this sector while reducing their dependence on foreign suppliers.

At the time of writing, the significant cost difference between carbon fibre (approximately €50/kg) and glass fibre (approximately €1.5/kg) necessitates distinct recycling approaches for these materials.

The MC4 project focuses on developing tailored short- and long-term technological solutions to address the recycling challenges for each material.

Overall, the MC4 project aims to establish short-term and long-term circular economy approaches:

- For carbon fibre: to re-use waste material directly in the production line and to recover the fibre from end-of-life parts for use in new products.
- For glass fibre: to re-use shredded material in new parts and to establish a new type of resin that allows the reshaping and thus repurposing of parts without separating the matrix and fibre.

This deliverable aims to present a set of educational materials, based on the wider content of the project, for use by partners FIDAMC, GAIKER, and VDL as training experts in the field. The educational materials include key methodologies for experts to consider when designing new circular products, and a relevant example of how to process Glass Fibre Reinforced Concrete (GFRC) to manufacture a piece of urban furniture.

## 2. EDUCATIONAL MATERIAL FOR DESIGN ENGINEERS: DESIGN METHODOLOGY (MANAGING COMPOSITES)

### 2.1 *Objective and Target Audience*

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This material aims to raise awareness and understanding of the basics of design methodology. It will help to identify which aspects of a product should be benchmarked (e.g., functionality, aesthetics, cost, performance). It will also guide in setting clear goals, such as improving efficiency, reducing production costs, or enhancing user experience. The target audience is represented by design engineers, architects, and students involved in design and manufacturing of final composite products.

### 2.2 *Educational Material Package*

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#### 2.2.1 *Educational format*

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It is provided as a Comprehensive PowerPoint Presentation: A visually engaging guide outlining the Design Methodology implemented by Managing Composites' technical staff for recyclability of composite materials.

These guidelines cover different topics as Project Background, Benchmarking, Design Specifications and Requirements and Design Process. During the project background, it is outlined the project context, objectives, historical background, necessity, scope, limitations, stakeholders, and expected impact. The focus is on the sustainability of composite materials, using the MC4 project as an example, emphasizing its goal of improving the circularity and competitiveness of the European carbon and glass fibre industry.

The Benchmarking covers methodologies, including defining objectives, analysing competitors, conducting SWOT analysis, identifying key performance indicators (KPIs), and collecting and analysing data. The section emphasizes the importance of comparing industry-leading products, assessing strengths and weaknesses, and using structured evaluation methods to enhance product design and competitiveness, with the MC4 project as a case study.

The Design Specifications and Requirements focus on defining specifications and requirements for product design, covering aspects such as general functions, compliance matrices, material selection, geometry, layout, mechanical properties, ergonomics, hardware, manufacturing processes, defects and inspection, assembly methods, product lifespan, and logistics. The section emphasizes structured decision-making to ensure performance, durability, and sustainability, using the MC4 project as a reference for applying these principles in composite material design.

The Design Process covers project phases, technology readiness levels (TRL), concept design, requirement analysis, business strategy, part design with focus on composite materials, joints and interfaces, layout and design for manufacturing (DFM), and design iterations. The section emphasizes optimizing materials, manufacturing processes, and structural integrity while ensuring efficiency and sustainability. The MC4 project serves as a practical example, illustrating how these methodologies contribute to the successful development of composite materials and products.

## **2.3 Key Messages and Assessment**

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### **2.3.1 Key Messages**

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The document gathers a comprehensive approach to sustainable composite material design, emphasizing the importance of defining project objectives, benchmarking industry standards, setting clear specifications, and optimizing manufacturing processes. By adopting these methodologies—such as designing for circularity, leveraging structured evaluation methods, and ensuring efficient resource use—can play a significant role in creating a more sustainable future for composites.

Collaboration across the value chain is crucial for successful implementation, enabling the industry to improve competitiveness, reduce environmental impact, and develop innovative solutions, as demonstrated by the MC4 project.

### **2.3.2 Success Measurement**

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In terms of assessment measurement, it is expected that improved designer awareness and understanding of the recyclability of composite materials will result in increased adoption of the methodology, in new product design and a strengthening of engagement with sustainable practices.

## **3. EDUCATIONAL MATERIAL FOR PROCESS AND PRODUCT ENGINEERS: CAE METHODOLOGY (MANAGING COMPOSITES)**

### ***3.1 Objective and Target Audience***

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This material aims to raise awareness and understanding how FEA (Finite Element Analysis) and CFD (Computational Fluid Dynamics) are applied during the dimensioning of products made up of recycled or recyclable composite materials. The MC4 glass fibre short-term activities are used as a practical example. These activities focus on developing a 3R resin reinforced composite with glass fibre.

A product demonstrator built is described to highlight the advantages and disadvantages of this recycled material approach compared to standard, non-recyclable products.

The target audience is represented by product engineers, and students involved in the design and manufacturing of final composite products.

### ***3.2 Educational Material Package***

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#### ***3.2.1 Educational Format***

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It is provided as a Comprehensive PowerPoint Presentation: A visually engaging guide outlining the Design Methodology implemented by Managing Composites' technical staff for recyclability of composite materials.

These material covers different topics as Fundamentals of FEA and CFD, as well as Composite Structural Simulations and Process Simulations that are key for a successful development of composite products. The Fundamentals of Computer-Aided Engineering (CAE), focusing on Finite Element Analysis (FEA) explain the discretization process, element types, and different types of analyses (linear, non-linear, and explicit), emphasizing their applications in product design and optimization. Key concepts such as boundary conditions, material behaviour, and numerical stability are covered, highlighting the importance of accurate meshing and computational efficiency for reliable simulations.

Computational Fluid Dynamics (CFD) explains how fluid behaviour is simulated using numerical methods. The section covers meshing techniques; turbulence models: (1) the Reynolds-averaged Navier-Stokes (RANS) model which resolves the mean flow and average out the turbulent fluctuations; (2) Large Eddy Simulation (LES) of forced isotropic turbulence at moderate Reynolds numbers; and (3) the Direct Numerical Simulation (DNS) model which resolves all the scales of the turbulent flows without any models or approximations; boundary conditions, and flow in porous media using Darcy's Law. It highlights the importance of selecting appropriate models and simulation parameters to ensure accurate predictions in aerodynamics, hydrodynamics, and thermal analysis.

The Structural Analysis section focuses on structural simulations within Finite Element Analysis (FEA). It gathers key steps such as geometry clean-up, meshing, model setup, analysis, and result reporting. Different material definitions are explained, including isotropic, orthotropic, and anisotropic materials, along with their mechanical properties. The document also goes into laminate definitions, discussing the stacking of

plies, stress calculations, and checks to ensure structural integrity. It highlights the importance of laminate balance, symmetry, and anti-symmetry to optimize mechanical performance.

The Process Simulations cover few processes key for the development of products within the MC4 project, focusing on Liquid Composite Moulding (LCM) methods such as Resin Transfer Moulding (RTM), Vacuum-Assisted Resin Infusion (VARI), and Resin Film Infusion (RFI). Each process is described in terms of preparation, vacuum application, resin infusion, curing, and demoulding. The section also explores flow in porous media, discussing permeability measurements and Darcy's law for modelling resin flow. Additionally, the document includes simulation examples, demonstrating how these principles are applied in engineering scenarios.

### **3.3 *Key messages and Assessment***

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#### **3.3.1 Key Messages**

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CAE is a powerful tool for design optimization, material selection, and problem-solving, enabling engineers to explore various design options to enhance aesthetics, functionality, and manufacturability, assess material performance for informed selection, and identify and resolve potential issues early to prevent costly rework.

#### **3.3.2 Success Measurement**

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In terms of assessment, it is expected that after completing this educational material, process and product engineers will demonstrate a marked improvement in their awareness and understanding of FEA and CFD fundamentals. This should lead to the practical application of CAE methodologies in new product designs, particularly for material selection and problem-solving.

## **4. EDUCATIONAL MATERIAL FOR CIRCULARITY: USING RECYCLED GFRC IN PRODUCT DESIGN AND MANUFACTURING (LAB23)**

### ***4.1 Objective and Target Audience***

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The main objective of this educational material is to raise awareness of the MC4 project and how it offers a valuable opportunity to innovate and safeguard manufacturing processes using recycled materials. It also aims to improve understanding among product and part designers regarding the use of recycled Glass Fibre Reinforced Concrete (GFRC) in their designs, promoting circular economy principles and sustainable material choices.

A focus on the circular process and the lay-up/casting manufacturing process is crucial for urban furniture manufacturers to fully exploit the potential of GFRC.

The target audience includes product designers, industrial designers, urban furniture manufacturing technicians, architects, and students involved in the design and manufacture of urban furniture.

### ***4.2 Educational Material Package***

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#### **4.2.1 Educational Format**

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The Educational Material Package is presented as a PowerPoint presentation, a visually engaging guide that outlines the entire recycled GFRC process. It follows the journey of the material from waste collection to the end-of-life reprocessing of a "Soul" bench, manufactured by LAB23.

The presentation begins with an introduction to the MC4 project and the recycled material in question, explaining the MC4 approach, the reasons for selecting GFRC, and the importance of its recycling. It then details the circular process chain, step-by-step, starting with waste collection – including current partnerships with VDL and plans for future sourcing from recycling centres.

The presentation then covers shredding, processing, composite preparation, moulding, finishing, installation, and finally, end-of-life reprocessing. Particular emphasis is placed on the specific techniques used for the "Soul" bench, such as hand lay-up and casting, with detailed explanations of resin preparation, including mixing ratios and curing processes.

The material properties and performance of recycled GFRC are then explored, providing data on its strength, durability, and aesthetic potential, while also addressing potential variations due to recycling and how to account for them in design.

Practical design considerations for recycled GFRC are offered, including guidance on material selection for different applications, principles for design for disassembly (with examples of separating components like armrests, chargers, and speakers), and an exploration of aesthetic possibilities, such as surface textures, colours, and finishes. Case studies showcase successful products made from recycled GFRC, including the "Soul" bench and its features, such as armrests and charging capabilities.

The environmental benefits of using recycled GFRC are quantified, highlighting reduced waste, lower energy consumption, and decreased reliance on virgin materials.

The presentation also emphasises the importance of collaboration across the value chain, from waste management companies to manufacturers and designers, encouraging engagement with the circular economy ecosystem.

Finally, future developments in recycled GFRC technology are discussed, including advancements in material processing and new applications.

#### **4.2.2 Direct Online Support**

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Support is provided by LAB23 website [www.lab23.it](http://www.lab23.it) and the direct email contact to the Technical Department of LAB23 [tecnico@lab23.it](mailto:tecnico@lab23.it) to ask direct questions on the concerned processes and to ask for supplementary materials such as videos and a Material Sample Kit. The kit contains samples of recycled GFRC in different forms (e.g., shredded, moulded, finished) to allow designers to explore the material first hand.

### **4.3 Key Messages and Assessment**

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#### **4.3.1 Key Messages**

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The Educational Material Package, which details the MC4 project's recycled GFRC process from waste collection to the "Soul" bench's end-of-life reprocessing, conveys several key messages.

Firstly, it demonstrates that recycled GFRC is a viable and sustainable material choice for product design. The journey of the material, as outlined in the package, illustrates its potential for reuse and its suitability for creating durable and aesthetically pleasing products.

Secondly, the material emphasises the importance of designing for circularity as an essential strategy for minimising environmental impact. By showcasing the complete lifecycle of the GFRC, from its initial use to its eventual reprocessing, the package reinforces the benefits of a circular economy approach.

Finally, the educational material highlights the crucial role of collaboration across the entire value chain for successful implementation of recycled GFRC. The MC4 project's partnerships, from waste collection to manufacturing and design, serve as a testament to the power of joined-up thinking and action in achieving a truly sustainable outcome.

#### **4.3.2 Success Measurement**

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In terms of assessment, the outlined entire recycled GFRC process implemented in the MC4 project (from waste collection to the end-of-life reprocessing of the "Soul" bench), will be measured by several key indicators.

Firstly, it is aimed to see an increased awareness and understanding of recycled GFRC amongst designers. This will be reflected in a greater appreciation of its properties, potential applications, and the benefits it offers in terms of sustainability. Secondly, and perhaps most importantly, success will be demonstrated by the actual adoption of recycled GFRC in new product designs. This tangible uptake of the material will signify that the educational package has effectively translated knowledge into action.

Finally, increased engagement with the circular economy ecosystem can be anticipated. This means designers, manufacturers, and other stakeholders actively collaborating and connecting to create a more sustainable and resource-efficient industry.

## 5. END PRODUCTS MANUFACTURED FROM RECYCLED COMPOSITE MATERIALS



The MC4 project's short-term and long-term recycling approaches are applied to create real-world products. As the project aims to develop tailored solutions for both carbon fibre (CF) and glass fibre (GF), the table showcases two examples of final products made using these materials described in the educational material Annex A and Annex C, highlighting the source of the materials (recycled or virgin), their composition, and key performance characteristics.

Specifically, it demonstrates:

- Glass Fibre (GF) Short-Term: The "Soul urban bench" exemplifies the short-term approach for GF, utilising shredded GF composite (a form of recycled material) in conjunction with virgin polyester resin. This aligns with the MC4 project's goal of re-using shredded GF in new parts.
- Glass Fibre (GF) Long-Term: The "Kayak" demonstrates the long-term vision for GF, using a GF composite based on a "3R resin matrix".

This refers to the project's aim of establishing a new type of resin that enables reshaping and repurposing without fibre separation. The kayak example highlights the benefit of this 3R resin in enabling a second life for the product.

The table also implicitly addresses the project's aims for carbon fibre recycling, though concrete examples are not provided in this specific table. It sets the stage for future development and implementation of short-term (re-use of waste in production) and long-term (fibre recovery from end-of-life parts) solutions for CF, which would be reflected in similar product examples in future iterations of this educational material.

	End product	Source parts/materials	Composition and Performance
Sports equipment	 Kayak	GF composite based on 3R resin matrix	One of the key benefits of developing the kayak with 3R resin is the ability to give it a second life
Urban furniture	 Soul bench	Shredded GF composite on virgin polyester resin	Composed of <b>at least 50% recycled content</b> and <b>100% recyclable</b> , it offers durability, weather resistance, and long-term outdoor performance.
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## 6. PRODUCT DATA SHEETS

Product Data Sheets, produced in collaboration with TECHTERA's designers, are included in the educational package as supplementary material. These provide the target audience with a comprehensive understanding of the two featured end products showcased as examples within the educational material. This aims to demonstrate the practical application of the MC4 project's innovations and encourage the adoption of circular economy principles in product design.

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PRODUCT DATA SHEET





MULTI-LEVEL CIRCULAR PROCESS CHAIN  
FOR CARBON AND GLASS FIBRE COMPOSITES

# SOUL BENCH

URBAN SEATING FOR THE FUTURE



Developed in Milan by LAB23, partner of the project MC4, the Soul Bench aims to reincorporate recycled composite material from end-of-life urban furniture, into a new, elevated product who blends design, functionality and sustainability.



### Bringing soul back to urban spaces

The name "Soul" reflects the bench's dual purpose: a soulful approach to sustainability and a unifying space for community gatherings.

More than just a piece of furniture; the Soul Bench is a functional work of art that transforms public spaces into welcoming and stimulating environments. Its design invites social interaction, encouraging community connection.

### By nature, for nature



#### Sustainability-driven

Incorporating recycled material from end-of-life urban seating, fully recyclable and eco-friendly production processes the Soul Bench represents a step toward achieving circular material loops, giving new life to end-of-life urban furniture.



#### Bio-inspired

Inspired by the gentle form of a sycamore seed, the Soul Bench blends nature-inspired design with sustainable innovation. Created in collaboration with Studio AG&P, its soft, fluid lines adapt effortlessly to both urban and natural settings.







Where functionality meets sustainable innovation



Composition

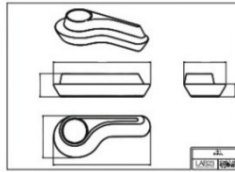
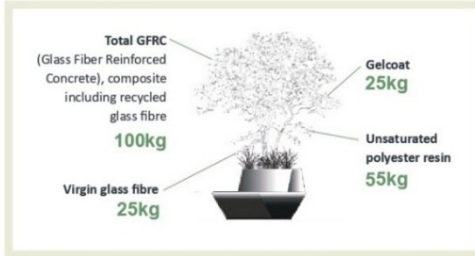
The Soul Bench uses a high-performance composite material developed by LAB23.

Composed of **at least 50% recycled content** and **100% recyclable**, it offers durability, weather resistance, and long-term outdoor performance.

This advanced material reflects LAB23's commitment to sustainability and circularity, reducing environmental impact while ensuring strength and reliability.



Material breakdown



Dimensions

Height.....1.4m  
 Width.....3.2m  
 Weight.....205kg

Features



INTEGRATED ARMRESTS



USB & WIRELESS CHARGING



ENVIRONMENTAL SENSORS



BLUETOOTH SPEAKERS



About LAB23

LAB23 offers a varied range of products – benches, bus or car canopies, bins, bollards, planters, bike racks, tree grates – for a total of about 200 products meant for both public and private clients. All products are characterized by a contemporary design combining rigid, essential shapes with soft and sinuous ones and high-quality, high-resistant materials that require very little maintenance costs. To achieve this, LAB23 chooses materials like galvanized steel, stainless steel, corten steel, hardwood, and HPRC (composite material).



About MC4

MC4 (Multi-level Circular Process Chain for Carbon and Glass Fibre Composites) is a European partnership aiming to establish circular approaches for carbon and glass fibre composites. After a 3 years implementation, MC4 will make the European carbon and glass fibre value chains more circular, independent and competitive.



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MORE INFORMATION



mc4-project.eu



PRODUCT DATA SHEET




MULTI-LEVEL CIRCULAR PROCESS CHAIN FOR CARBON AND GLASS FIBRE COMPOSITES

# KAYAK & PADDLE

ROWING BEYOND COMPOSITE WASTE



Developed by Managing Composites with contributions from CIDETEC and Chomarat, the MC4 Kayak demonstrates the potential of recyclable composites in sporting goods. Built using glass fiber and CIDETEC's 3R epoxy resin, it combines durability with circularity. At end-of-life, key components can be reshaped into new paddles, closing the loop on composite waste.

## Unlocking composite recyclability with a sustainable epoxy

The **3R resin** is an environmentally friendly epoxy vitrimeric system developed by CIDETEC in recent years. Containing reversible bonds, this system exhibits stress relaxation at high temperatures (vitrimeric behavior), enabling composites to be reshaped, repaired, and ultimately recycled into new products rather than being landfilled or incinerated, a systemic challenge faced by composite materials.

This system enables to re-use composite parts without separating the fiber from the matrix, thus offering the possibility to recycle through a re-shaping process to create new components for different applications.

With this demonstrator, Managing Composites, with support from CIDETEC and Chomarat, explores the recycling GFRC with the 3R resin to highlight how reprocessable composites are able to maintain the high level of performance properties required in demanding applications while reducing waste.

### About the 3R resin



Recyclable



Reprocessable



Repairable

## The kayak: an ideal demonstrator

### ✓ A strong case for circularity

*A product to reconnect with nature and outdoors yet demonstrating a relatively short lifespan and difficult conventional recyclability.*

### ✓ High potential for recovery

*An elongated shape and large surface facilitating an efficient reuse, enabling sections to be repurposed into new components, such as paddles.*

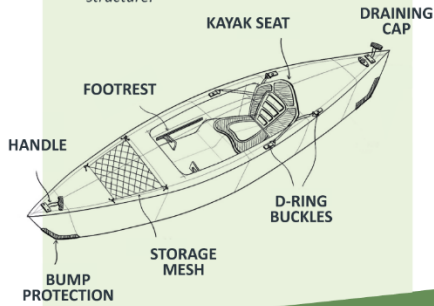
### ✓ A demanding yet 3D-ready test

*A requirement for high mechanical performance, balancing rigidity, durability and lightness, while aligning with 3R resin compatible manufacturing process (infusion).*

### A versatile, convenient and functional product

Hybrid between a recreational sit-on-top and a touring kayak, this model is stable, easy to use and fun while also comfortable and useful in many different settings such as longer-distance traveling. It is meant to be used by a single person, and it has several added features to make it fully functional.

*Features include: a storage mesh, two handles to carry the kayak; a seat to improve ergonomics and comfort with two adjustable footrests to allow the use by people of different sizes (mounted on specifically designed composite brackets), and lastly, a draining cap to account for any water that could be leaked inside the structure.*



### Composition

#### KAYAK

##### 40wt%

**3R Resin**  
made of 3 different components

##### 60wt%

**Glass fibre**  
Biaxial squared twill of 360gsm, developed by Chomarat, used as reinforcement fibre



#### PADDLE

##### BLADES

**Recycled glass fibre composite**  
Blades cut-outs from a discarded kayak and reshaped through thermoforming with the 3R resin

##### FIXING INTERFACE

**Block of glass fibre and epoxy composite**  
To fix blades to rod and reinforce weak areas, machined and adhered between

##### ROD

**Carbon fiber**  
2m long as a connection between the blades, due to its lightness and excellent mechanical properties



### Manufacturing process

- 1

Development of a new resin in compliance with specifications of envisioned manufacturing process (infusion)
- 2

Selection of most adequate fibre sizing to be used in combination with 3R resin (with Chomarat and 3B Fibreglass)
- 3

Manufacturing by combination of 3R resin and glass fibre fabrics for mechanical characterization and demonstrators' designs validation
- 4

Thermoforming trials on 3R composite laminates to explore process limitations and define processing window for recycling of kayak parts into paddles

### About Managing Composites

Managing Composites is an engineering company specialized in the development of composite materials from early-stage prototype design to small series production. Its main activity focuses on automotive, aerospace, marine and sport and leisure industry. Managing Composites also have a strong R&D activity, tending to develop and spread the intensive use of sustainable materials for a greener industry.



### About MC4

MC4 (Multi-level Circular Process Chain for Carbon and Glass Fibre Composites) is a European partnership aiming to establish circular approaches for carbon and glass fibre composites. After a 3 years implementation, MC4 will make the European carbon and glass fibre value chains more circular, independent and competitive.

#### MORE INFORMATION



[mc4-project.eu](http://mc4-project.eu)



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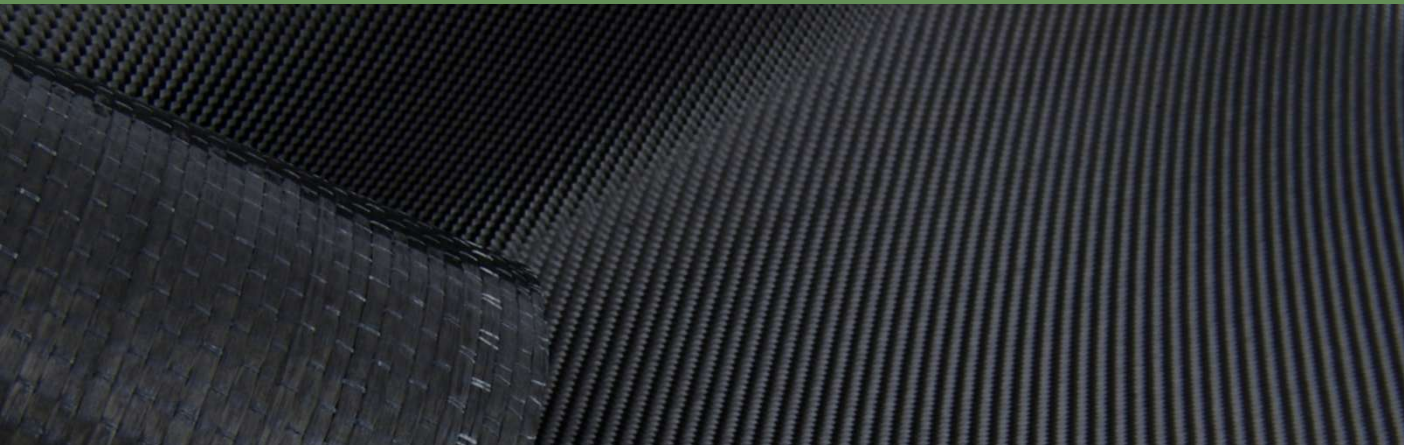
## 7. SUMMARY & CONCLUSIONS

This comprehensive educational package will empower designers and engineers to adopt an effective design methodology for composite material recyclability. It will also equip process and product engineers with a CAE (Computer-Aided Engineering) methodology, enabling product designers to make informed material selection decisions. Ultimately, this will contribute to a more sustainable future by encouraging the uptake of recycled GFRC (Glass Fibre Reinforced Concrete) and other relevant recycled and recyclable composite materials. By showcasing practical applications through the 'Kayak & Paddle' and 'Soul bench' examples, supported by Product Data Sheets, the educational material demonstrates the MC4 project's research and development efforts, promoting the adoption of circular economy principles in product design.



**Multi-level Circular  
Process Chain for Carbon  
and Glass Fibre Composites**

# ANNEX A



**Funded by  
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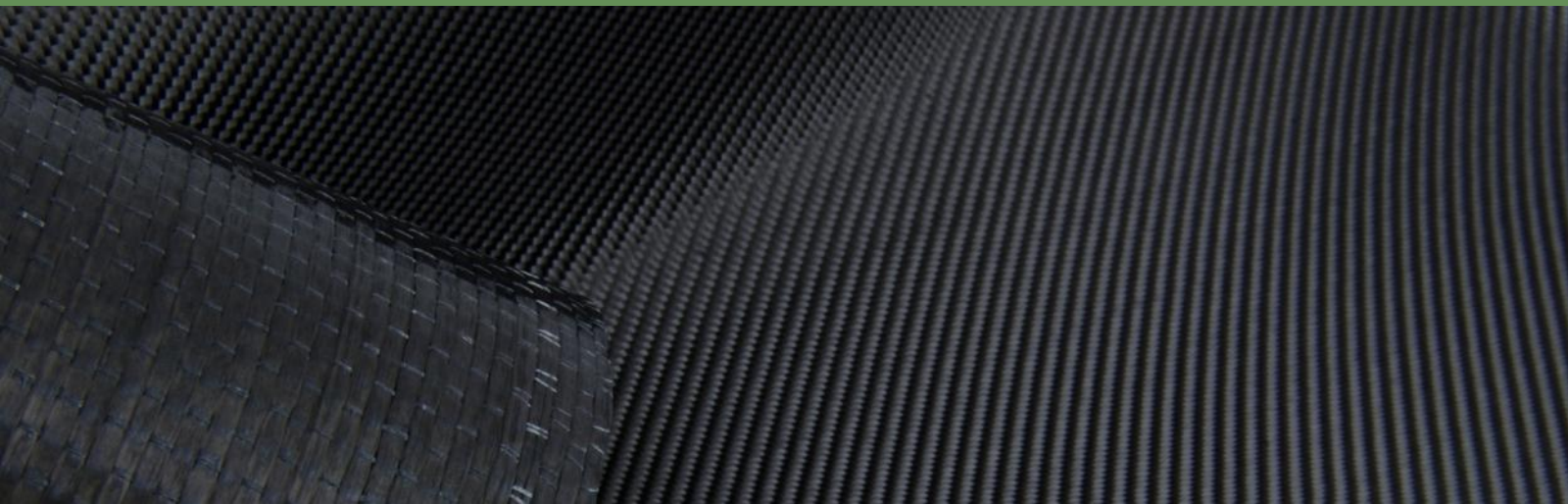
**Multi-level Circular  
Process Chain for Carbon  
and Glass Fibre Composites**

# **Educational Material for Design Engineers: Design Methodology**

Madrid 05/02/2025



**Funded by  
the European Union**



- 1. Project Background**
- 2. Benchmarking**
- 3. Design Specs & Requirements**
- 4. Design Process**

# 1. Project Background



Funded by  
the European Union

## PROJECT BACKGROUND



## PROJECT CONTEXT

- Identify the problem, need, or opportunity.
- Describe the industry, market, or environment.
- Mention key stakeholders and their interests.

## PROJECT CONTEXT

KAYAK EXAMPLE:

**Need:** Recyclability of composite materials

**Industry:** Composite materials


**Stakeholders:**



## PURPOSE & OBJECTIVES



Why is the  
project  
happening?



Primary Goals  
& Expected  
Outcomes

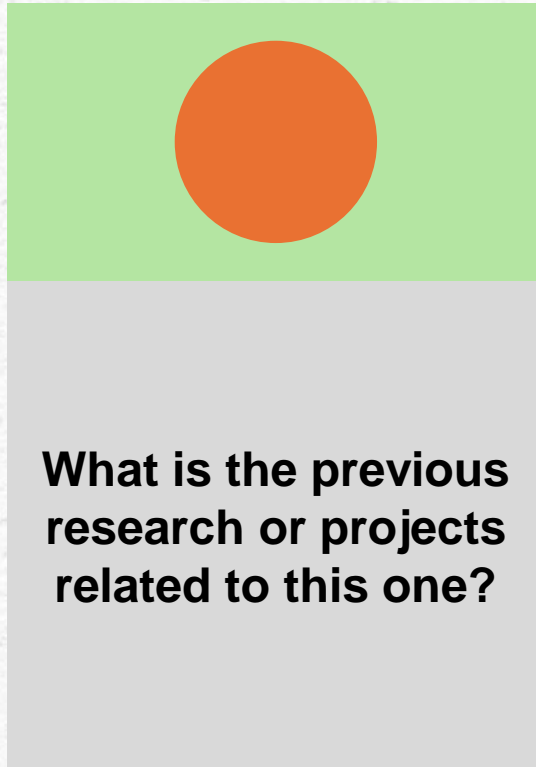
## PURPOSE & OBJECTIVES

KAYAK EXAMPLE:

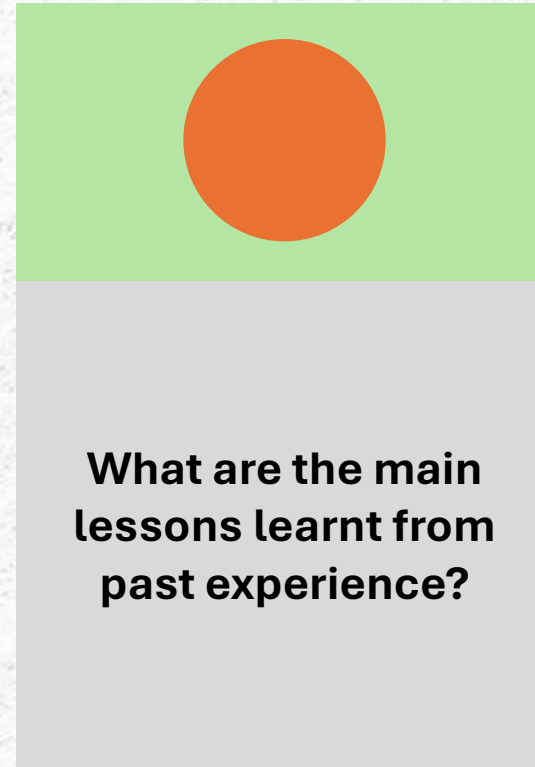
**Why is it happening & expected outcomes:**

- MC4 (Multi-level Circular Process Chain for Carbon and Glass Fibre Composites) is a European partnership aiming to establish circular approaches for carbon and glass fibre composites.
- After a 3 years implementation, MC4 will make the European carbon and glass fibre value chains more circular, independent and competitive.

## HISTORICAL BACKGROUND



**What is the previous research or projects related to this one?**



**What are the main lessons learnt from past experience?**

## NEED FOR THE PROJECT

**WHAT IS THE IMPORTANCE OF THE PROJECT?**  
SUPPORT WITH DATA TO BACK THE CLAIM

## NEED FOR THE PROJECT

### KAYAK EXAMPLE

MC4 glass fiber - short term activities are based on the development on the 3R resin with glass fiber as reinforcement. Building a product demonstrator will highlight pros and cons against the standard non recyclable product

## SCOPE & LIMITATIONS

- What is included in the project and what isn't?
- What are the constraints? Budget, time, resources etc.

## SCOPE & LIMITATIONS

### KAYAK EXAMPLE

- Establishing a multi-level circular process for carbon and glass fibre composites, with processes developed for both a short term and a long-term impact on the industry
- Developing performant and economically realistic processes that are adapted to the specificities of the two value chains
- Giving to the European industry the means to master and own its patented manufacturing processes of recycled materials
- MC4 will be achieved in March 2025

## STAKEHOLDERS & ROLES

**WHO IS INVOLVED IN THE PROJECT & WHAT ROLES DOES EVERYONE HAVE?**

## STAKEHOLDERS & ROLES

### KAYAK EXAMPLE

**WHO IS INVOLVED IN THE  
PROJECT & WHAT ROLES DOES  
EVERYONE HAVE?**

In order to achieve its objectives, MC4 gathers 16 partners covering the whole value chains: process developers, material manufacturers, end users manufacturing the composite parts.

## BENEFITS & IMPACT



VALUE OF THE  
PROJECT



ECONOMIC,  
SOCIAL OR  
ENVIRONMENTAL  
BENEFITS

## BENEFITS & IMPACT

### KAYAK EXAMPLE:

Currently, up to 40% of the material is wasted in the production process, and after a lifetime of 15 to 30 years, 98% of the material ends up in a landfill with no hope to be recycled . With a yearly use of about 110.000 tons of carbon fibre composites parts and 4,5 million tons of glass fibre composites, the environmental impact needs to be addressed.

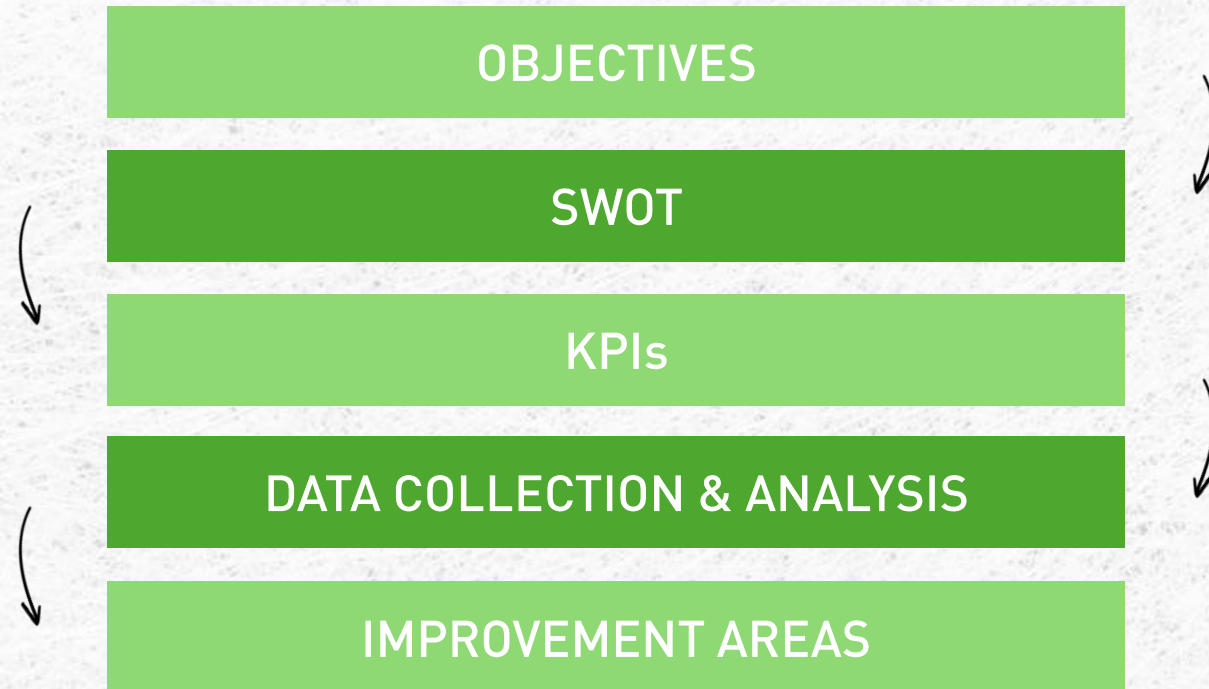
In addition to these environmental issues, the current competitive position of Europe in these value chains needs to be improved in order to be less dependent from foreign sources. 80% of the virgin carbon and glass fibre manufacturing is done outside of Europe, and when the manufacturing is done in Europe, its technologies are often licensed from foreign countries.

## 2. Benchmarking



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## BENCHMARKING



## OBJECTIVES

- Identify what aspects of the product you want to benchmark (e.g., functionality, aesthetics, cost, performance).
- Set clear goals, such as improving efficiency, reducing production costs, or enhancing user experience.

## COMPETITORS/ REFERENCE PRODUCTS

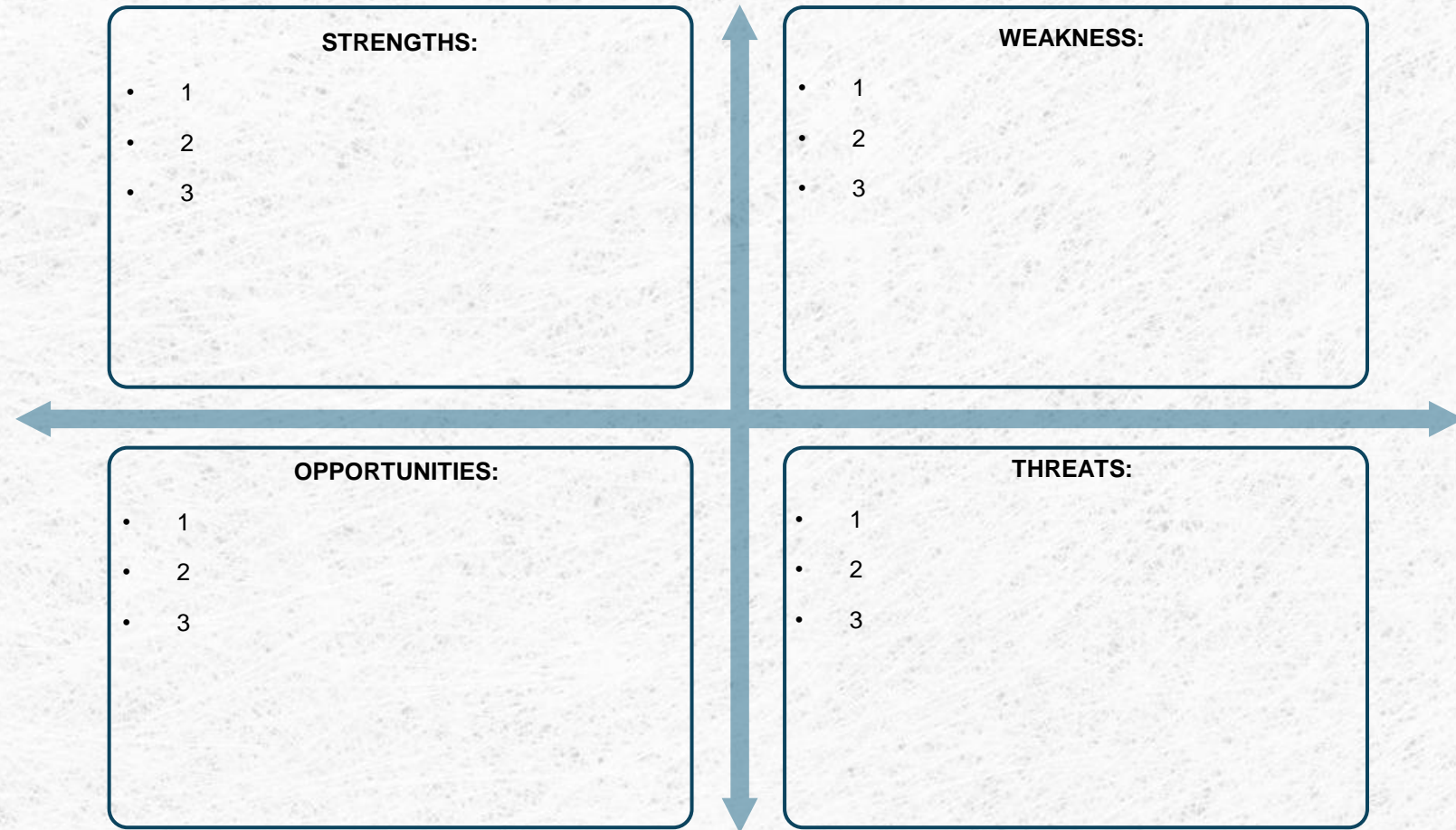
- Research direct and indirect competitors.
- Select industry-leading products with similar features or market positioning.
- Consider benchmarking against best-in-class products even outside your industry.

## SWOT Analysis

It is a strategic tool used to evaluate an organization's **Strengths, Weaknesses, Opportunities, and Threats**. In **benchmarking**, it helps compare an organization's performance against industry leaders or competitors to identify areas for improvement.

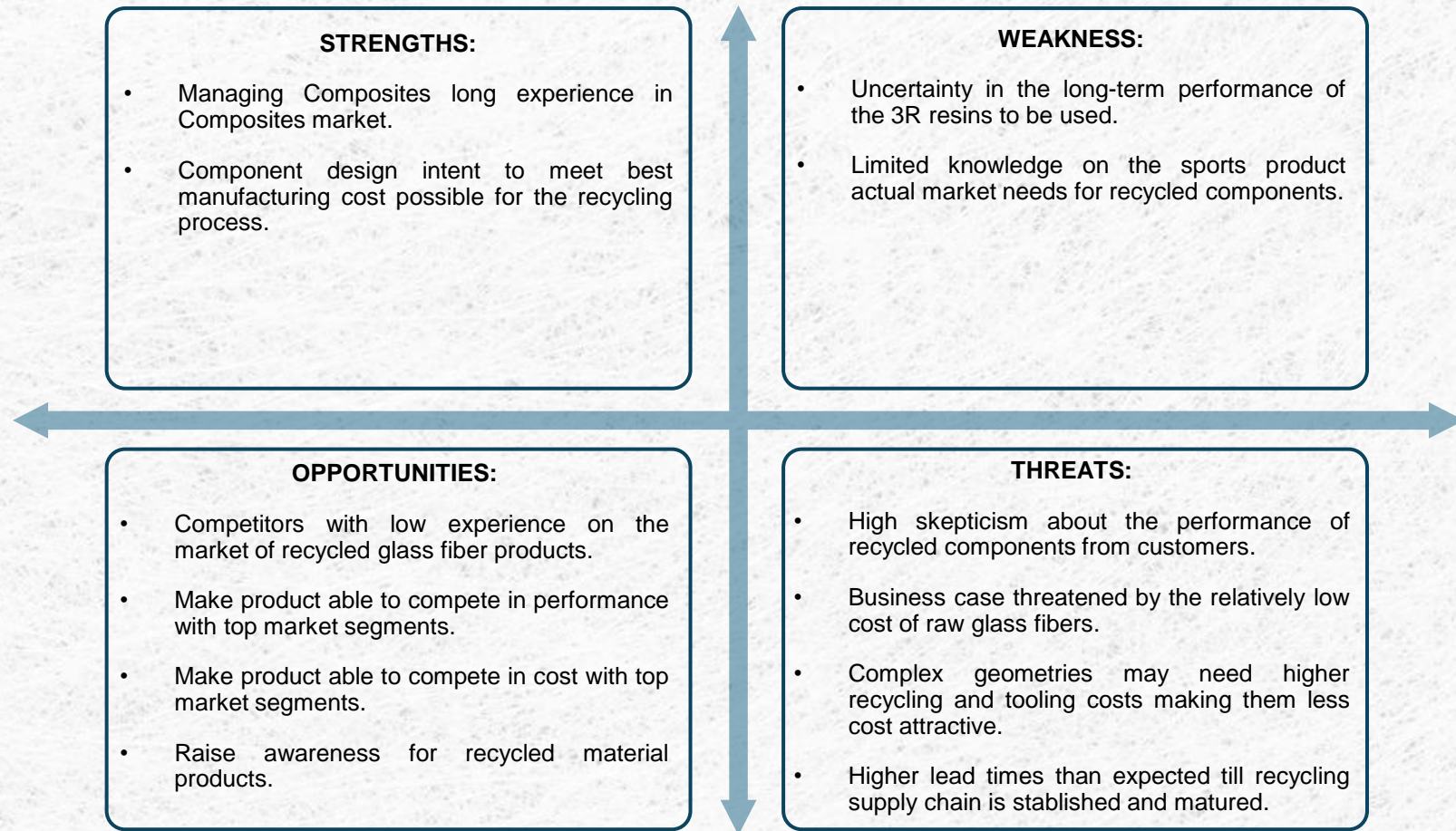
- 1. Strengths** – Identify internal advantages compared to competitors (e.g., strong brand, skilled workforce, advanced technology).
- 2. Weaknesses** – Pinpoint internal shortcomings revealed through benchmarking (e.g., outdated processes, low efficiency).
- 3. Opportunities** – Discover market trends, innovations, or gaps where the organization can improve (e.g., new technology adoption).
- 4. Threats** – Recognize external risks highlighted in benchmarking (e.g., competitive pressure, economic downturns).

## SWOT Analysis



## SWOT Analysis

### KAYAK EXAMPLE



## KPIs

- Define measurable criteria, such as:
- Performance Metrics (speed, durability, energy efficiency)
- Design Aspects (ergonomics, aesthetics, materials)
- Cost Factors (manufacturing cost, retail price)
- User Experience (ease of use, customer reviews)

## KPIs Table

### KPI 1

- Evaluation method for our KPI and ways to measure the criteria defined

### KPI 2

- “”

### KPI 3

- “”

### KPI 4

- “”

### KPI ...

- “”

## KPIs

### KAYAK EXAMPLE

#### Tooling investment required

- Low or Zero
- Mid
- High

+ Suited for a single demonstrator unit  
-

#### Piece cost

- Low
- Mid
- High

- Business case for recycled products  
+

#### Currently recycled?

- Yes: Currently recyclable and recycled products available on the market.
- No: There may be potential for recycling but is not currently recyclable

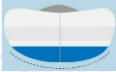
#### Mechanical properties


- Abrasion resistance
- Impact/puncture resistance
- Stiffness

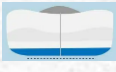
## KPIs

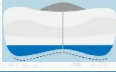
### KAYAK EXAMPLE

#### Hull Shapes: Given by the cross section in contact with water

- Round hull:** 

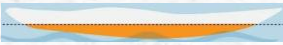
Pros: Typically give good maneuverability. Good balance between stability and speed. Suited for rough waters or anywhere with changing conditions.  
Cons: Good allrounder but not the best for speed or stability.
- V-Shaped hull** 

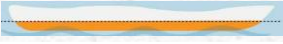
Pros: Allows for sleek shapes (large aspect ratios): Best shape for speed.  
Cons: Worst shape for roll stability and maneuverability. Suited for calm waters only.
- Flat hull:** 

Pros: Allows for good stability.  
Cons: Not great maneuverability. Suited for calm waters only. Not the best shape for high speeds.
- Tunnel hull:** 

Pros: Best shape for stability.  
Cons: Not great maneuverability or speed.

#### Pitch stability aka “rocker”: Given by hull curvature in longitudinal section.

- More rocker:** 

Pros: More end-to-end curvature allows for easier maneuverability.  
Cons: Less pitch stability more difficult to keep a straight track (tracking).
- Less rocker:** 

Pros: Suited for tracking.  
Cons: Compromises maneuverability.

#### Aspect ratio

- High Aspect ratio:** Typically kayaks above 5m. Suited for speed and good tracking.
- Low aspect ratio:** Typically kayaks below 2.5m. Suited for good maneuverability.

## DATA COLLECTION & ANALYSIS

- Gather qualitative and quantitative data through:
  - Product testing and reverse engineering
  - User feedback and surveys
  - Market research reports
  - Competitor product specifications and patents
- Create comparison tables or visual charts to identify strengths and weaknesses.
- Identify gaps in your product's performance or design.
- Look for trends and best practices in competitors' products.

## DATA COLLECTION & ANALYSIS

Product type	
	<u>Main Characteristics</u>
• 1	
• 2	
• 3	

### Main brands making the product

- Brand 1
- Brand 2
- Brand 3
- Brand ...

## KPI's

KPI 1	Where does this product fall within our KPI's?
KPI 2	“”
KPI 3	“”
KPI 4	“”
KPI 5	“”
KPI 6	“”
KPI ...	“”

## RELEVANT POINTS

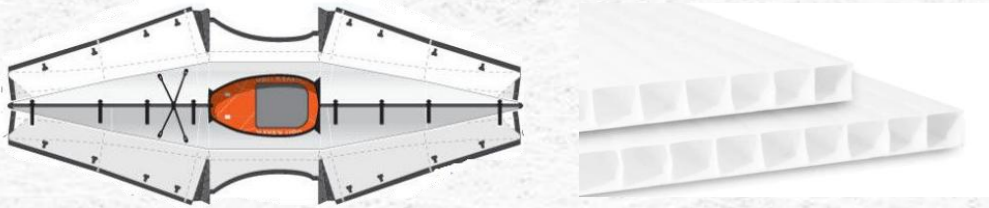
- ✓ Other relevant information regarding the product

## DATA COLLECTION & ANALYSIS – KAYAK EXAMPLE

**Foldable sheet kayak**

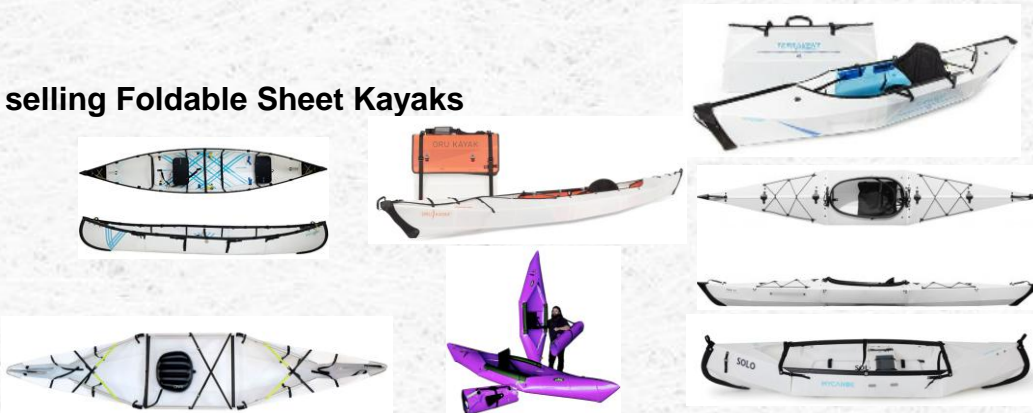
Materials typically used:

- 5mm thickness corrugated Polypropylene panel.
- PPE sheet.
- Polyethylene sheet.



### Main brands selling Foldable Sheet Kayaks

- [Terravent](#)
- [Orukayak](#)
- [Mycanoe](#)
- [Tucktec](#)
- [ONAK](#)
- [Nortik](#)



## KPI's

<b>Tooling investment</b>	Zero or near zero
<b>Piece cost</b>	Low to Mid (Ranging from 300€ to 2000€ retail prices)
<b>Currently recycled?</b>	No but there is potential
<b>Mech properties</b>	Low abrasion resistance. Mid/low impact resistance. Low stiffness.
<b>Hull Shapes</b>	Flat (low roll)
<b>Rocker</b>	Generally low rocker (low pitch)
<b>Aspect ratios</b>	Mid range. Minimum width is limited to approx.. 65cm due to the need for various sheets on the sides to achieve longitudinal stiffness or adding protection to uncovered Sharp edges around user.

## RELEVANT POINTS

- ✓ Targets beginner to mid level customers for recreational and leisure use.
  - Used for recreational kayaking.
  - Designed for low angle paddling.
  - All available in the 2.5 to 5m range.
  - Flat and Wide hull, typically more than 65cm wide for good stability
  - Aspect ratio is not a main design driver as they are not designed for speed.
- ✓ Good potential for a one-off demonstrator unit due to No tooling or virtually no tooling required
- ✓ Good business case for recycled product market due to Mid range piece cost

## IMPROVEMENT AREAS

- Highlight opportunities for product innovation.
- Determine features or design aspects that can be optimized.
- Consider cost-saving alternatives without compromising quality

# 3. Specs & Requirements



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## SPECS & REQUIREMENTS

- General Functions
- Specifications

## GENERAL FUNCTIONS

### COMPLIANCE MATRIX

- WHAT IS IT AND WHEN IS IT DONE?

- The Compliance Matrix is a table base tool used to analyze and list the requirements of a project or activity.
- It also addresses the status of compliance towards a set of requirements
- The time to start with a Compliance Matrix is at the beginning of the Project. Ideally even in a quotation phase.

- WHY IS THIS IMPORTANT?

- It addresses the technical and contractual requirements of the project.
- It helps to frame the works required and it can be used to discuss Out of Scopes or Scope Creeps along the project development.

- WHY IS RESPONSIBLE FOR IT?

- This is normally managed by Contract and Project Manager; however, it is responsibility of everyone to share thoughts on how to comply on an efficient way towards a requirement and raise new requirements that may not be captured.

## GENERAL FUNCTIONS

### COMPLIANCE MATRIX

- INDUSTRY?
  - The industry is moving rapidly towards the usage of more and more Subject Matter Experts to resolve difficult problems, this is an opportunity to companies to apply their know-how to resolve them.
  
- WHERE CAN I START?
  - Commercial and technical discussions with customers and suppliers.
  - High level requirements from Conceptual Data, Functional requirements, Tolerances, Designs...
  - Statement of Work, RFIs, RFQs...
  
- WHEN IS IT CLOSED?
  - This should be closed at project Kick Off but as really imposes, this could be an open document until the time of Specification Closure.

## WHICH INDUSTRY THIS IS RELEVANT TO?

- Motorsports
- Automotive
- Aerospace
- Marine
- Military
- Space

## WHICH WORLD MARKETS ARE INVOLVED?

- SPAIN
- EUROPE
- UK
- USA
- MIDDLE EAST
- RUSSIA

## DELIVERY CONDITIONS?

- exWORKS
- OTHERS

## WHICH CURRENCIES INVOLVED (Lifespan)?

- EUR
- GBP
- USD

## RAW MATERIALS?

- Local distributors
- Long distances
- Standards vs Bespoke

## GENERAL FUNCTIONS

### COMPLIANCE MATRIX

REQUIREMENT	STATUS	RISK	ACTION	OWNER

## GENERAL FUNCTIONS

### BRAINSTORMING

**WHAT ITEMS DO WE HAVE TO  
KEEP IN MIND WHEN DEFINING A  
SPEC?**

## ITEMS

- MATERIAL SELECTION
- SIZE & GEOMETRY
- LAYUP
- INSERTS, FIXINGS & HARDWARE
- FUNCTION
- MANUFACTURING
- DEFECTS & INSPECTION
- UNITS, COSTS & TIME
- ASSEMBLY
- PART LIFE
- LOGISTICS

## MATERIAL SELECTION

**HOW DO WE CHOOSE THE  
CORRECT MATERIALS?**

## MATERIAL SELECTION

- WHAT MATERIALS DO WE HAVE AVAILABLE IN-HOUSE? OR IN OUR SUPPLY-CHAIN? DO THEY FIT?
- ARE THERE ANY SIMULATIONS AVAILABLE? MANUFACTURING OR PERFORMANCE?
- ARE THERE ANY INDUSTRY LIMITATIONS?
- DO WE HAVE A LAYUP OR MATERIAL SPEC?

## MATERIAL SELECTION – KAYAK EXMPLE: Fiber & Resin

PRODUCT CHARACTERISTICS		
Kayak	60 wt.% - 3R Resin	The MC4-F12B resin system developed by CIDETEC is made of 3 different components
	40 wt.% - Glass Fiber	The Glass Fiber used as a reinforcement in the composite material is a biaxial squared twill of 360gsm developed by Chomarat
Paddle	Recycled GF Composite	The blades of the paddle are first cut from a Kayak who's life has ended and then due to properties of the 3R Resin, the cutouts are reshaped through a thermoforming process.
	Fixing Interface	To fix the reshaped blades into the Carbon Fiber Rod and reinforce the weak areas of the blade, a block of glass fiber and epoxy composite will be machined and adhered between
	Carbon Fiber Rod	A 2m carbon fiber rod is used as connection between the two blades due to its lightness and excellent mechanical properties

## MATERIAL SELECTION – KAYAK EXMPLE: Adhesive

- **Adhesive used:** ET5429 Slow Composites Structural Epoxy Adhesive
- **Why:** PERMABOND® ET5429 is a thixotropic two-part adhesive with excellent resistance to impact and vibration. The controlled flow properties as well as its ease of mixing and application, enables the adhesive to be used where gap filling or vertical application is required. Permabond® ET5429 has been found to provide exceptional performance even at elevated temperatures. It is ideal for use in construction of composite assemblies.
- **Properties:**

**Physical Properties of Uncured Adhesive**

	ET5429 A side	ET5429 B side
Chemical composition	Epoxy Resin	Polyamine Hardener
Appearance	White	Black
Mixed appearance	Charcoal black	
Viscosity @ 25°C	20rpm: 200,000 mPa.s (cP)	20rpm: 60,000 mPa.s (cP)
	2rpm: 300,000 mPa.s (cP)	2rpm: 150,000 mPa.s (cP)
Specific gravity	1.0	1.0

**Typical Curing Properties**

Mix ratio	2:1 by volume 2:1 by weight
Maximum gap fill	5 mm 0.2 in
Usable / pot life @23°C 10g mixed	2-4 hours
Handling time	23°C: 6-10 hours
Working strength	23°C: 24 hours
	60°C: 1 hour
Full cure	23°C: 72 hours
	60°C: 2 hours

**Typical Performance of Cured Adhesive**

Shear strength* (ISO4587)	Mild Steel: 23-28 N/mm <sup>2</sup> (3335-4060psi)
	Aluminium: 26-31 N/mm <sup>2</sup> (3770-4495psi)
Peel strength (aluminium) (ISO4578)	Stainless Steel: 25-30 N/mm <sup>2</sup> (3625-4350psi)
	Carbon Fibre: >25 N/mm <sup>2</sup> ** SF (>3625psi)
	FRP Glass/Polyester: >6 N/mm <sup>2</sup> *** SF (>870psi)
	FRP Glass/Epoxy: 18-22 N/mm <sup>2</sup> (2610-3190psi)
	PEEK: 4-5 N/mm <sup>2</sup> (580-725psi)
	PA6 30% filled: 4-6 N/mm <sup>2</sup> (580-870psi)
	PVC: >3 N/mm <sup>2</sup> ** SF (>435psi)
	Polycarbonate: 3-4 N/mm <sup>2</sup> (435-580psi)
	150-230 N/25mm (33-51 PIW)
	Impact strength (ASTM D-950)
Hardness (ISO868)	65-75 Shore D
Elongation at break (ISO37)	<5%
Glass transition temperature Tg	50-60°C (122-140°F)
Dielectric strength	15-25 kV/mm

\*Strength results will vary depending on the level of surface preparation and gap.  
 \*\*SF Denotes substrate failure

## GEOMETRY & SIZE

1

### PRACTICAL IMPLICATIONS

CAN I MOVE THE COMPONENT IN THE FACTORY? DOES IT FIT IN MY AUTOCLAVE?

2

### MOLDS

WHAT MATERIAL WILL I BUILD THE MOLDS IN?

3

### MATERIALS

HOW MUCH OF STRUCTURAL AND CONSUMABLES WILL I NEED?

## GEOMETRY & SIZE

### KAYAK EXAMPLE

- To reshape parts of the Kayak into the Paddle, the Kayak must have a predominance of soft shaped (close to planar) surfaces.
- It must be designed with a balance between maneuverability and straight-line performance.
- Good hydrodynamic performance. This is related to the design of the bottom of the kayak.
- Inserts, extra components, Adhesive behavior, seat, footrest, sealed chamber fixing (strips) – Sketch inserts, y cores\*

## LAYUP

**HAVE WE RECEIVED A LAYUP WITH  
ORIENTATIONS AND EVERYTHING  
NECESSARY?**

## LAYUP

● PATTERNS

● REINFORCEMENTS

● SYMMETRICAL

● SURFACE FINISH

● DIRECTION

● INSERTS

● GRAMMAGE

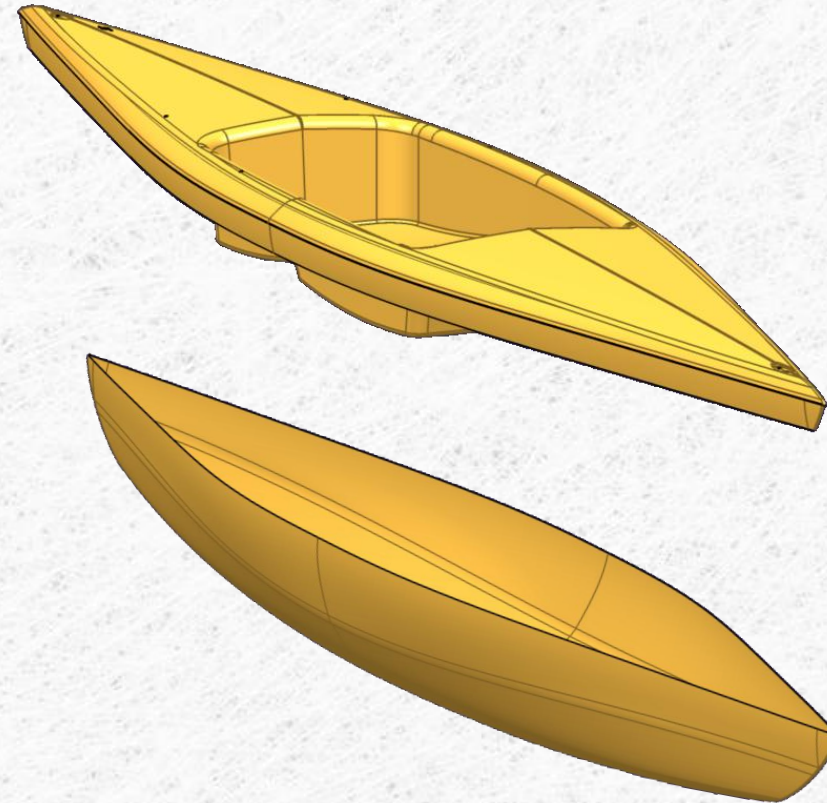
● OTHER MATERIALS  
APPLIED

## LAYUP

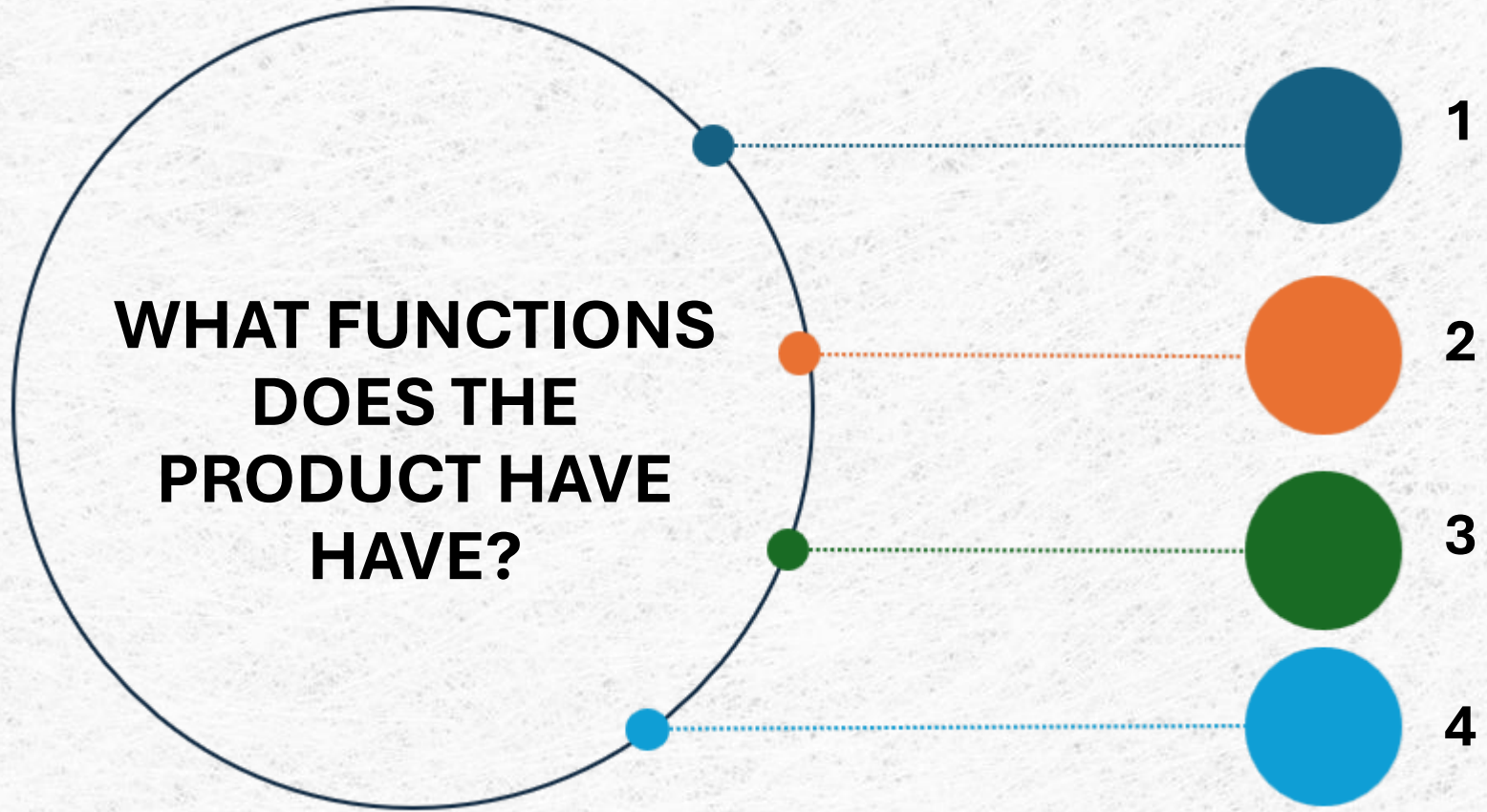
### KAYAK EXAMPLE

#### ZONE 1

PLY	PREPREG TYPE	DIRECTION	Z1
1	360gsm T1x1	0/90°	X
2	360gsm T1x1	±45°	X
3	360gsm T1x1	0/90°	X
4	360gsm T1x1	±45°	X
5	360gsm T1x1	0/90°	X

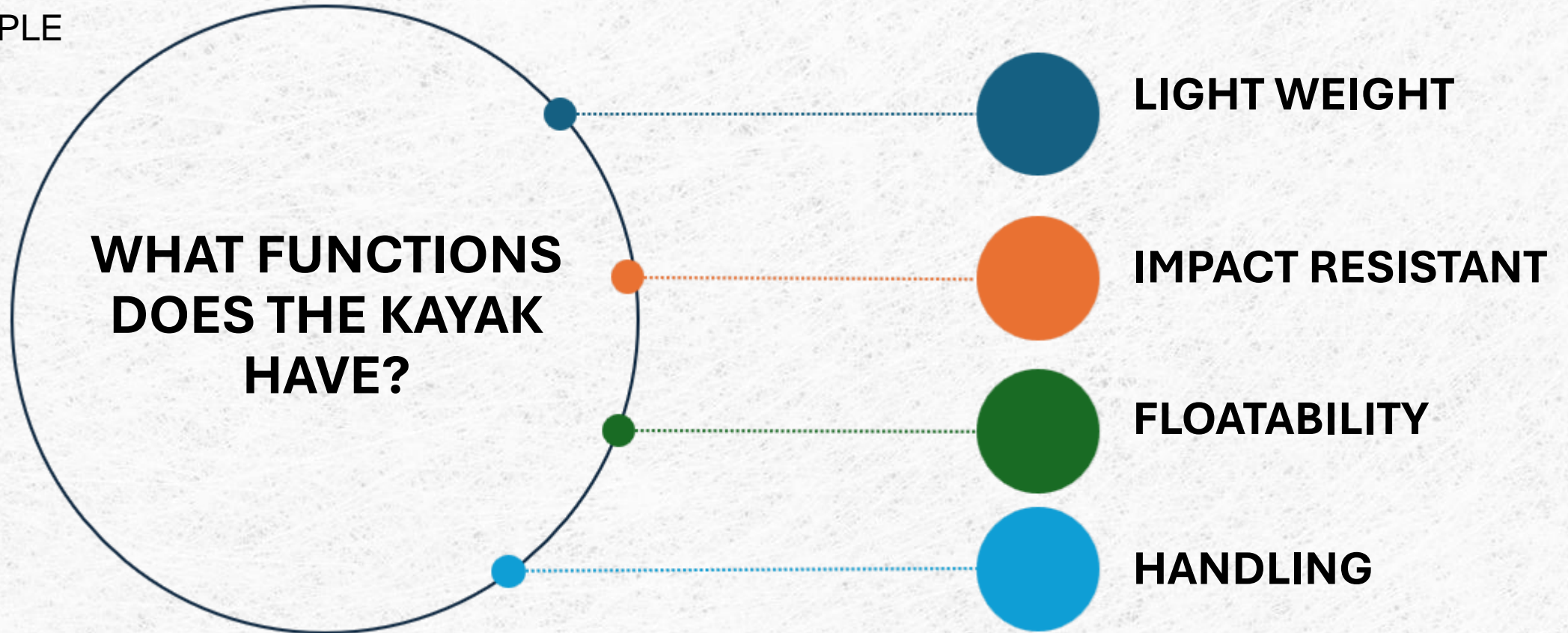


## MECHANICAL REQUIREMENTS



## MECHANICAL REQUIREMENTS

KAYAK EXAMPLE



## MECHANICAL REQUIREMENTS

**WHAT SPECIFIC FUNCTIONS  
DOES THE PRODUCT NEED TO  
FULFILL?**

## MECHANICAL REQUIREMENTS – KAYAK EXAMPLE

- Minimum weight of 12 Kg (as specification of Olympic Category of Sprint) – expected around 20 kg.
- Withstand at least 120 Kg (one person)
- Be able to withstand an impact at 7 km/h with no puncture/cracks.
- Be able to withstand an impact at 12 km/h with no catastrophic damage.
- Impact direction definition – frontal, bottom scratching
- 1.5 y 1.8 mm thickness laminates
- Withstand loads from handles on both sides of the kayak when lifted.
- Be able to withstand saltwater environment.
- Floatability
- Maneuverability & straight-line performance

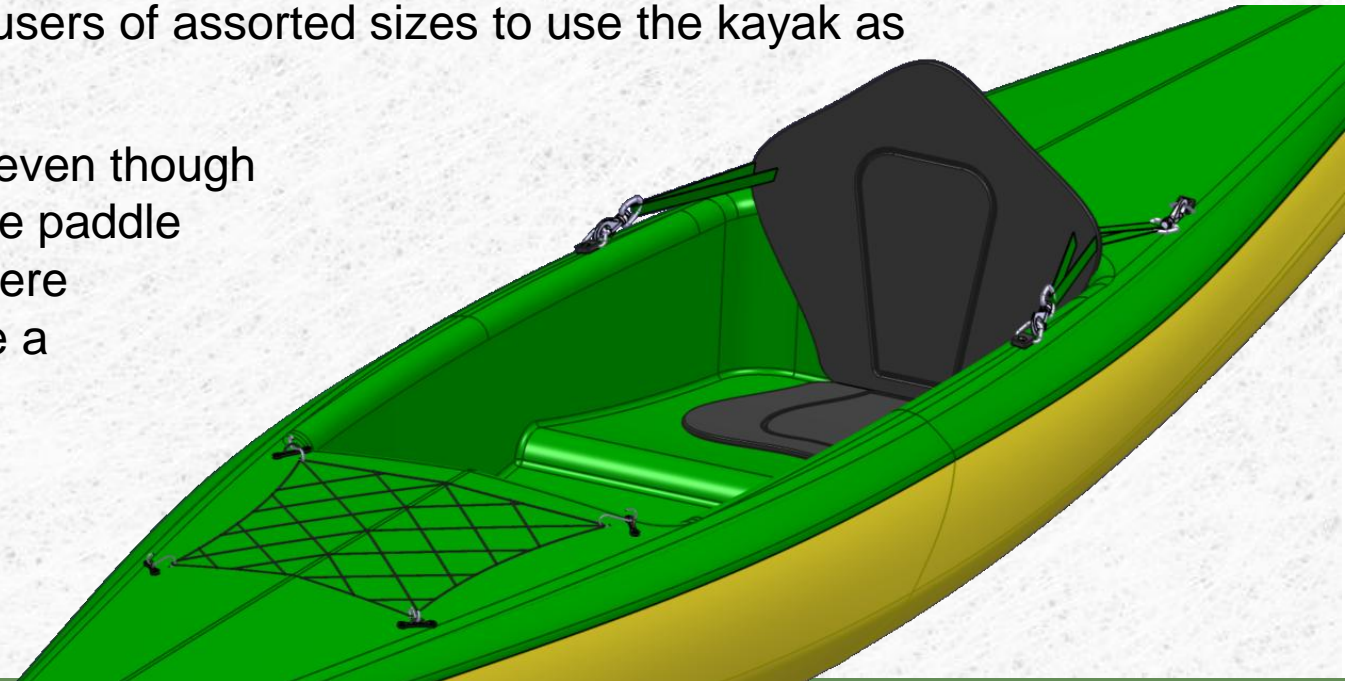
## ERGONOMICS

- Ergonomics are crucial in product design because they ensure that a product is comfortable, efficient, and safe for users. A well-designed, ergonomic product enhances usability, reduces strain, and improves overall user satisfaction. Here's why ergonomics matter in product design:

- 1. Enhances User Comfort**
  - Reduces physical strain and discomfort
  - Fits natural human movements and postures
  - Prevents fatigue during prolonged use
- 2. Improves Efficiency & Productivity**
  - Minimizes unnecessary effort or movement
  - Makes interactions more intuitive and seamless
  - Reduces errors and frustration
- 3. Prevents Injuries & Health Issues**
  - Lowers the risk of repetitive strain injuries (RSIs)
  - Reduces musculoskeletal disorders (MSDs)
  - Promotes long-term well-being
- 4. Increases User Satisfaction & Adoption**
  - A comfortable product is more likely to be used correctly
  - Enhances brand reputation and customer loyalty
  - Reduces returns and complaints
- 5. Addresses Diverse User Needs**
  - Accommodates different body sizes, strengths, and abilities
  - Ensures accessibility for people with disabilities
  - Adapts to various environments and conditions

## ERGONOMICS – KAYAK EXAMPLE

- Flat and soft surfaces are needed to cutout material that later will be reshaped as paddles. This means that the focus is not only on comfort, but also on the recyclability of the material, which limits the geometries and complicates the ergonomics of the cockpit.
- To ensure the size of the cockpit, a 180 cm tall dummy was used as a standard, having in mind an adjustable footrest would be added later to allow for users of assorted sizes to use the kayak as well.
- The seat and the back rest were designed very flat, even though that is not the most ergonomic shape, but to favor the paddle cutouts later. The angles of the back rest and seat were adjusted by using the dummy as reference to ensure a comfortable, but stable sitting position for paddling.



## HARDWARE & STANDARDS – INSERTS & FIXINGS

● TITANIUM

● GLASS FIBRE

● ALUMINIUM

● CO-MOULDED

● STEEL

● BONDED

● CORROSION

● OTHER

## HARDWARE & STANDARDS

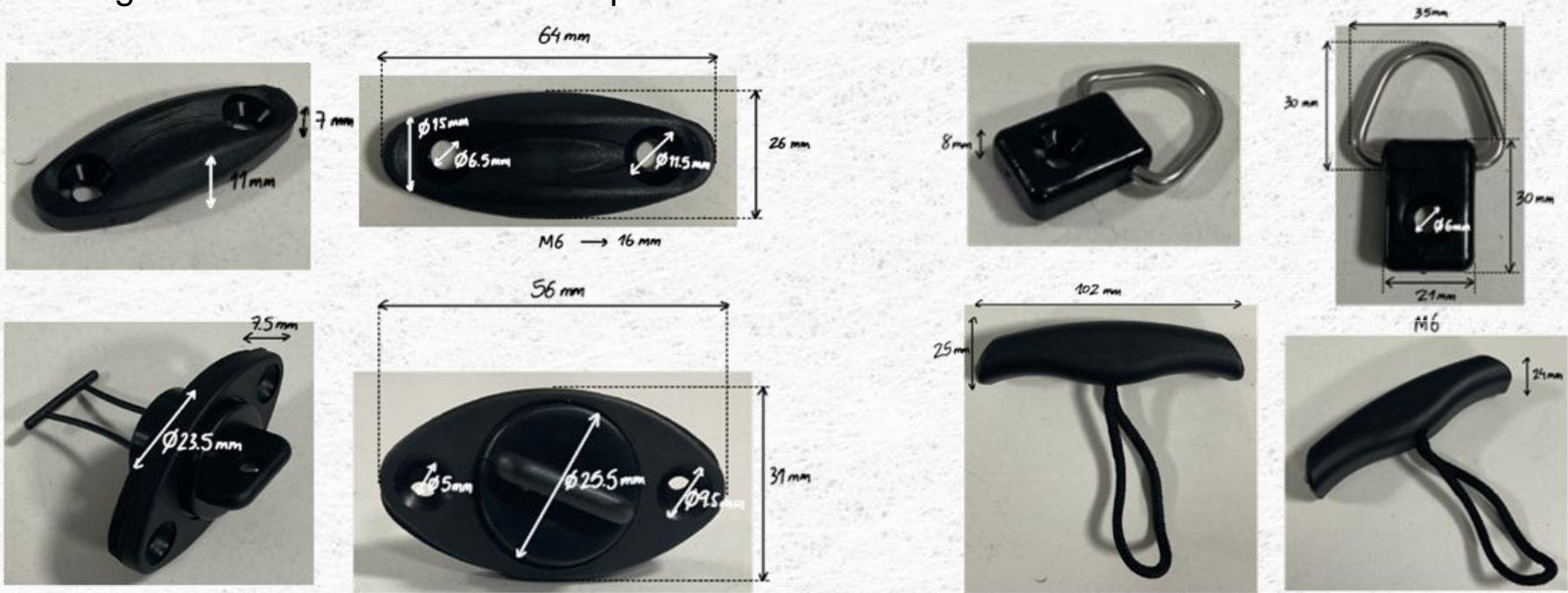
The kayak composite structure is complemented with some external components that cover the needs that the basic geometry by itself lacks, such as comfort and functionality. These hardware & external components are the following:

- Stainless steel Blind Rivet Nuts
- Storing mesh
- Hull draining cap.
- Kayak handle
- Bumps protections
- Seat Attachments
- Ergonomics – Feet and back angle

## HARDWARE & STANDARDS

### KAYAK EXAMPLE – MEASUREMENTS

The external components were bought through online retailers not specialized in kayak elements, which ended up being the easiest way, but not all the required dimensions necessary to complete the design. The pieces, once received, had to be measured to design the interfaces with the composite structure.

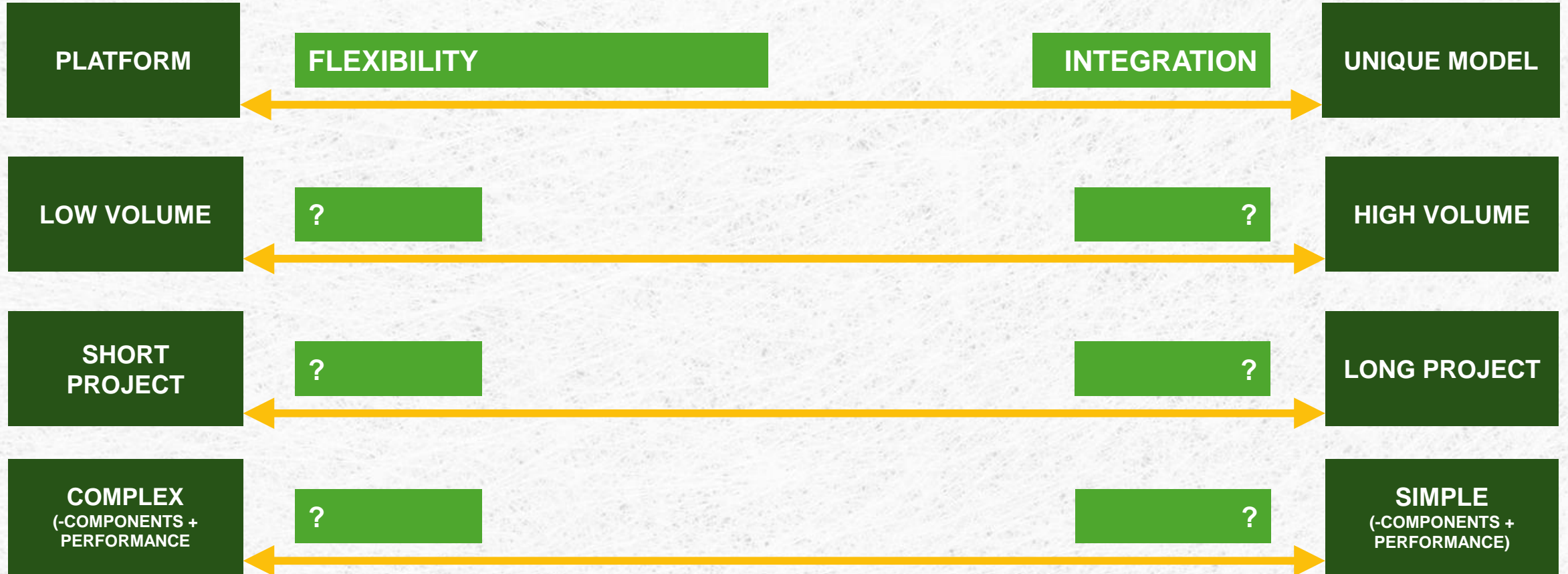


## MANUFACTURING

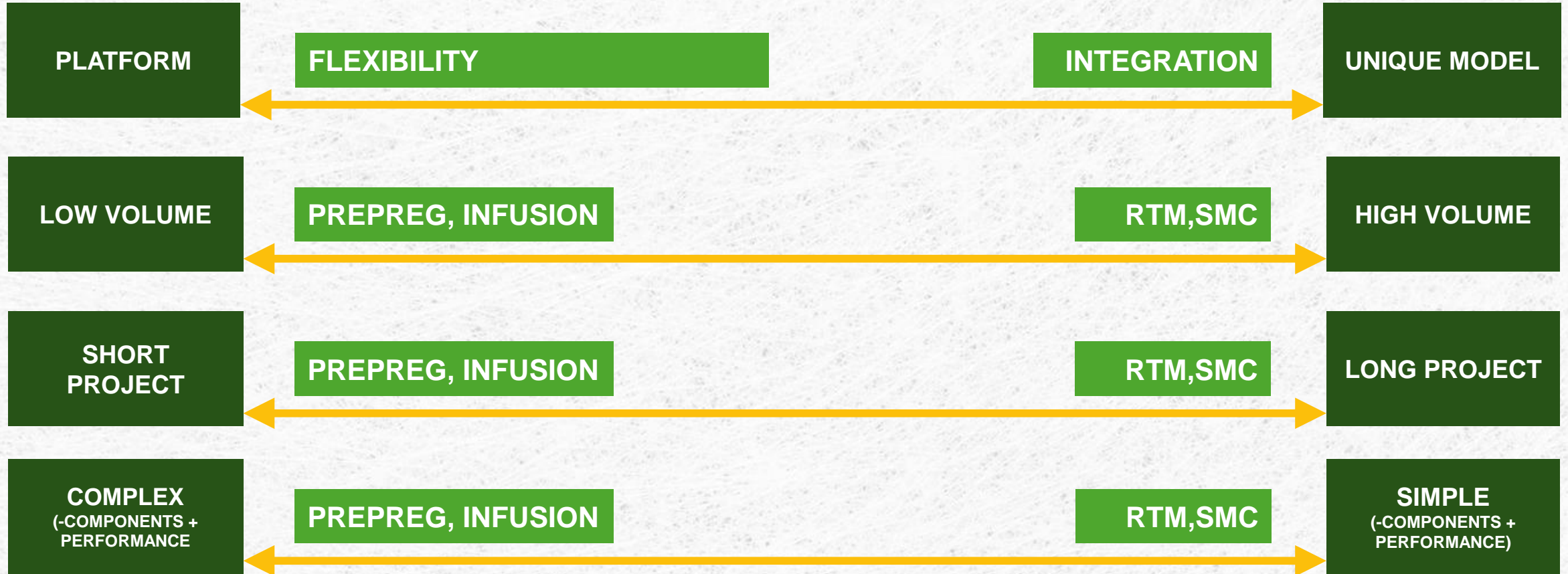
**WHAT DO WE TAKE INTO ACCOUNT  
BEFORE?**

**MATERIALS OR MANUFACTURING?**

## MANUFACTURING



## MANUFACTURING Depending on cadence and performance requirements



## DEFECTS & INSPECTION

**AS A MATTER OF FACT, COMPONENTS NEVER ARE PERFECT**

SO, WHAT TOLERANCES DO WE ALLOW FOR?

## DEFECTS & INSPECTION

**MOREOVER...**

ARE WE SUPPOSED BY SPEC TO USE ANY KIND OF INSPECTION METHOD?

## ASSEMBLY

### MECHANICAL JOINTS



### ADHESIVE JOINTS



## ASSEMBLY

### MECHANICAL JOINTS

SIMPLER

CLEANER

TIGHTENING TORQUE

NOT PERMANENT

### ADHESIVE JOINTS

UNIFORM LOAD DISTRIBUTION

SEAL FROM ENVIRONMENT

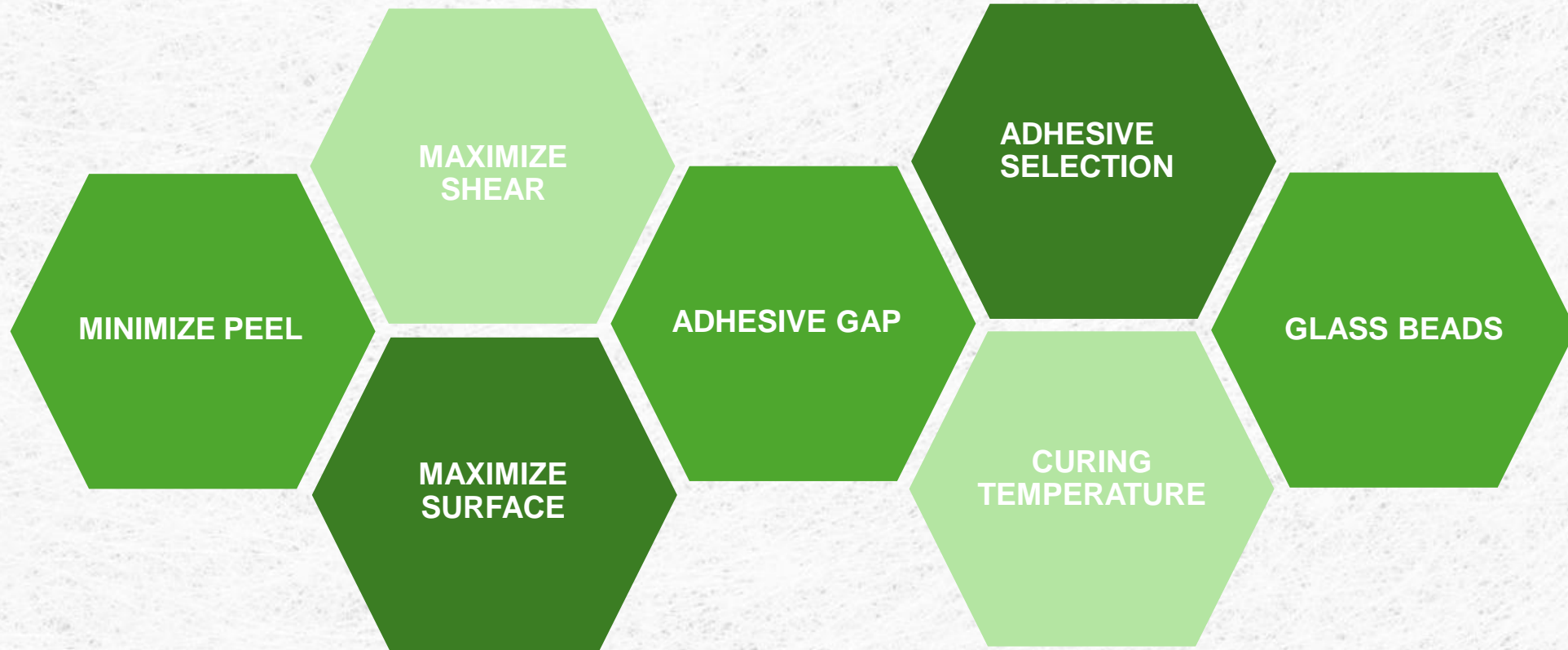
AESTHETICS

WEIGHT REDUCTION

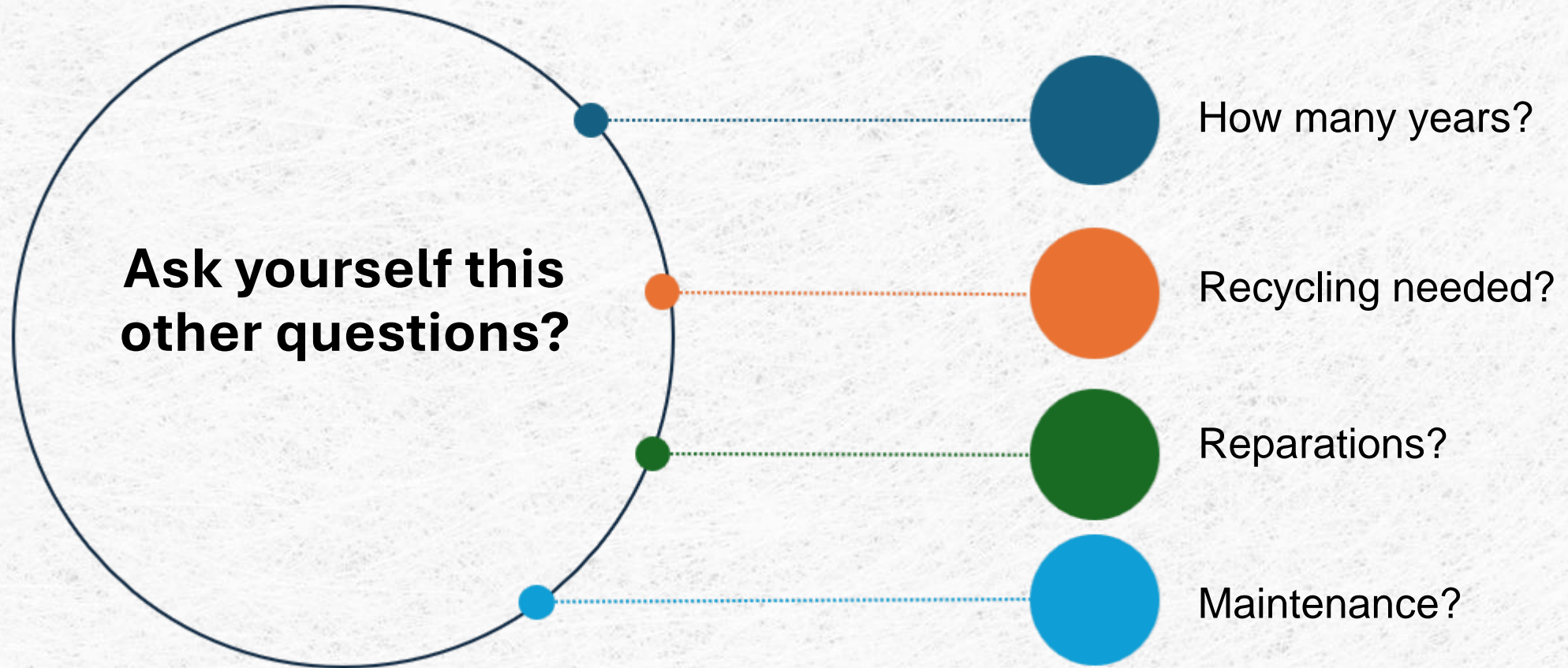
NO HOLES

ABSORB TOLERANCES

## ASSEMBLY



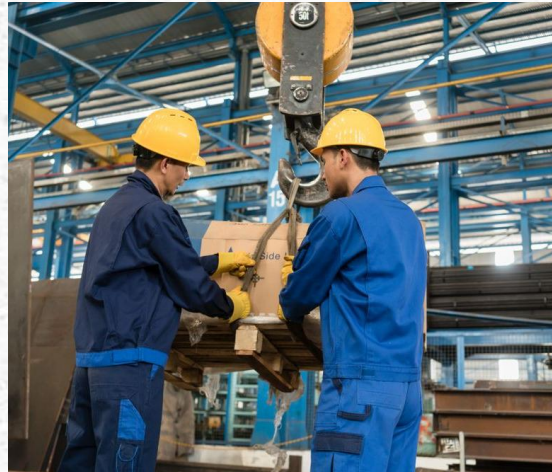
## PRODUCT LIFE



## LOGISTICS



**STORAGE  
REQUIREMENTS**



**HANDLING  
REQUIREMENTS  
AND GUIDE**



**TRANSPORTATION**

## 4. Design Process

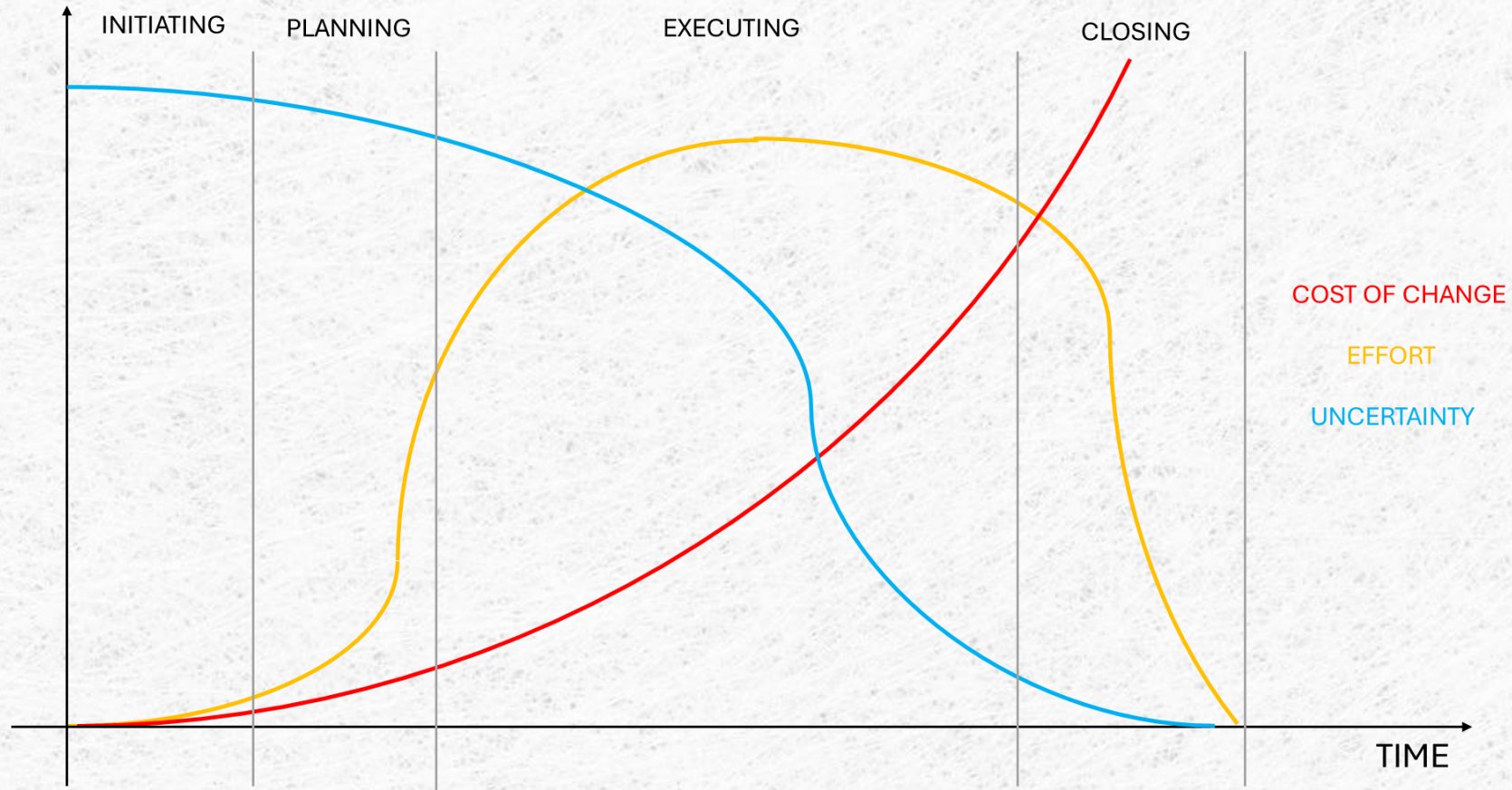


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## DESIGN PROCESS

### PROJECT PHASES

The initial phases of the project should be mainly focused in dissipating the uncertainties



## DESIGN PROCESS

### PROJECT PHASES

#### Technology Readiness Level (TRL)

Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress.

## DESIGN PROCESS

### PROJECT PHASES

#### Technology Readiness Level (TRL)

TRL 0 – Idea

TRL 1 – Basic Research

TRL 2 – Technology Formulation

TRL 3 – Needs Validation

**TRL 4 – Large Scale Prototype** ← **Example:** MC4 Kayak got all the way to this level

TRL 5 – Small Scale Prototypes

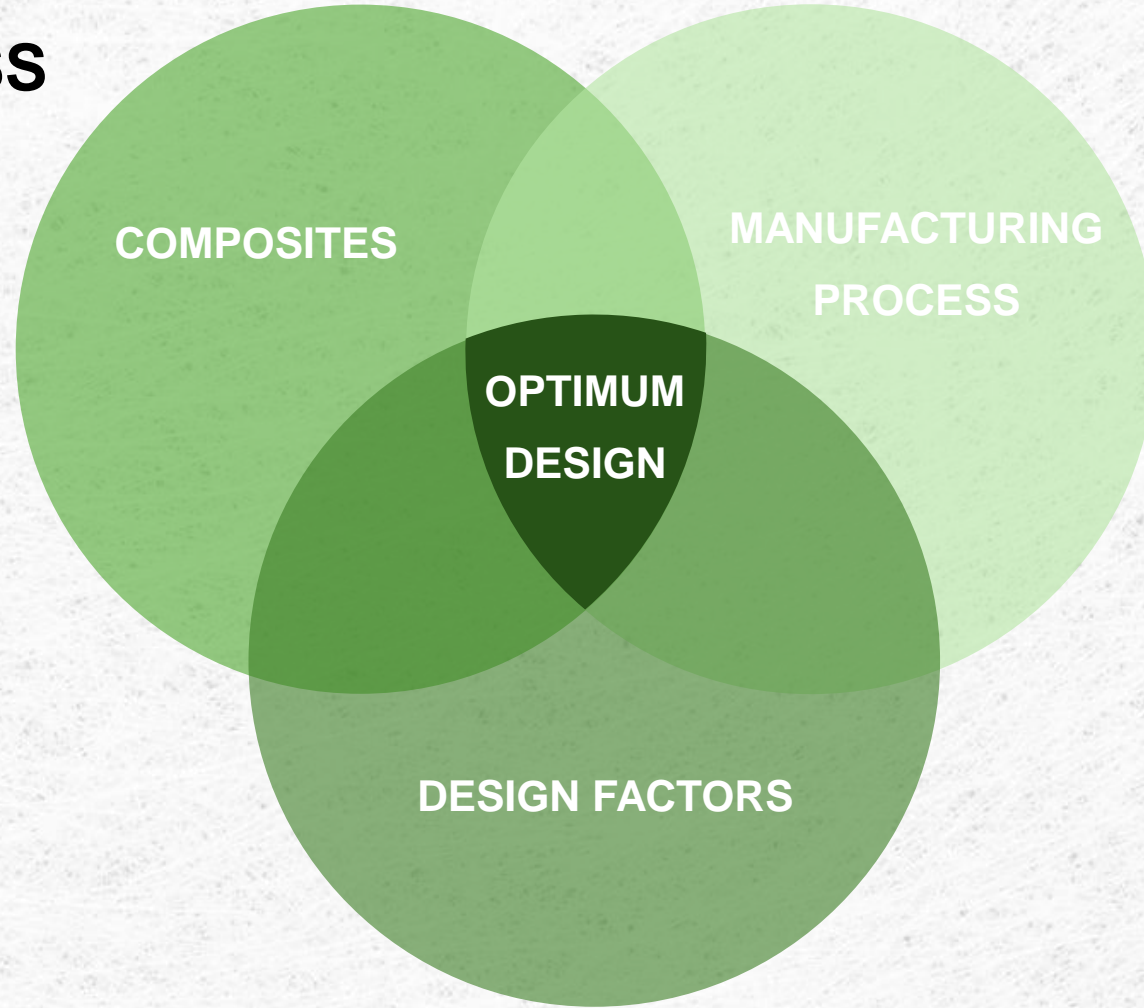
TRL 6 – Prototype System

TRL 7 – Demonstration System

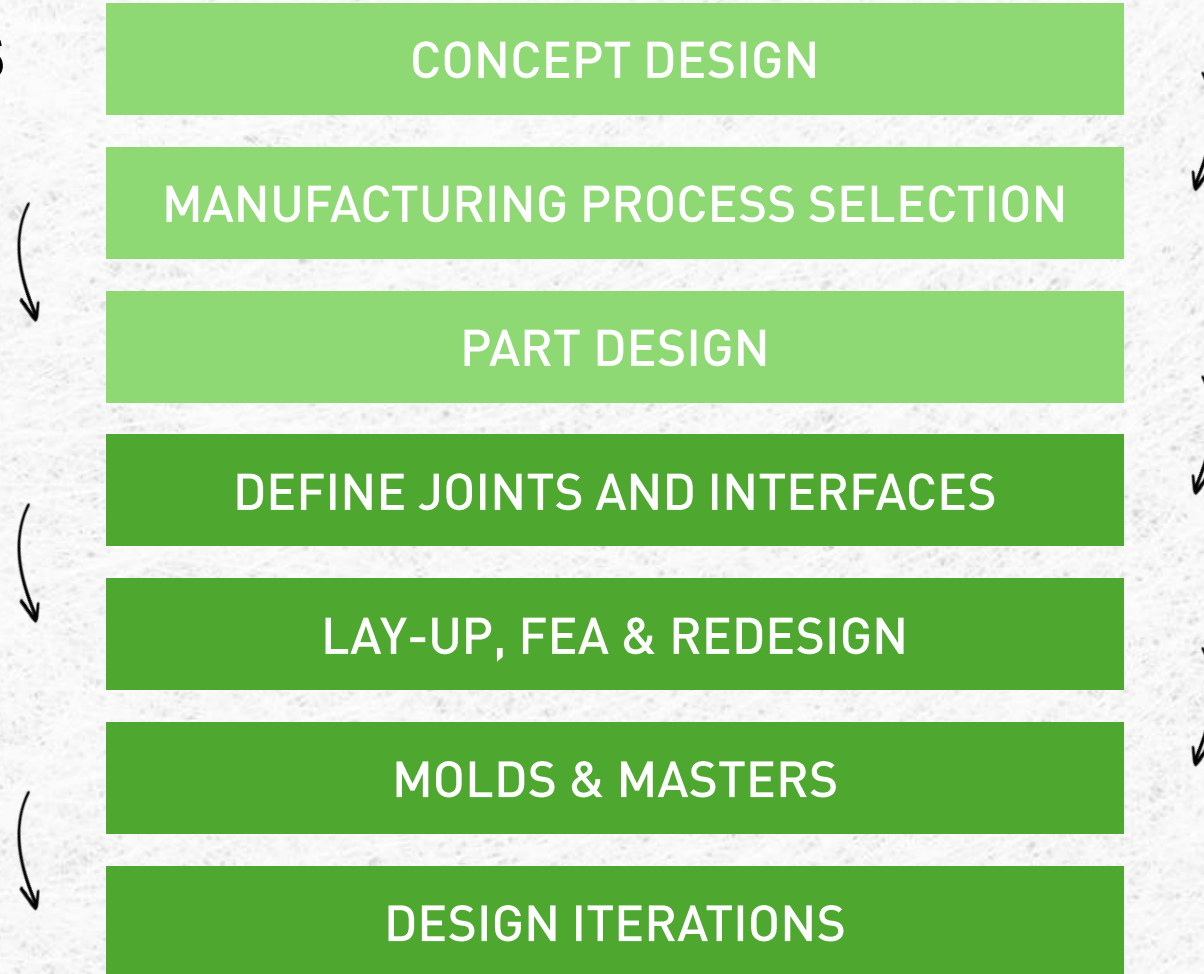
TRL 8 – First of a Kind Commercial System

TRL 9 – Full Commercial Application

## DESIGN PROCESS



## DESIGN PROCESS



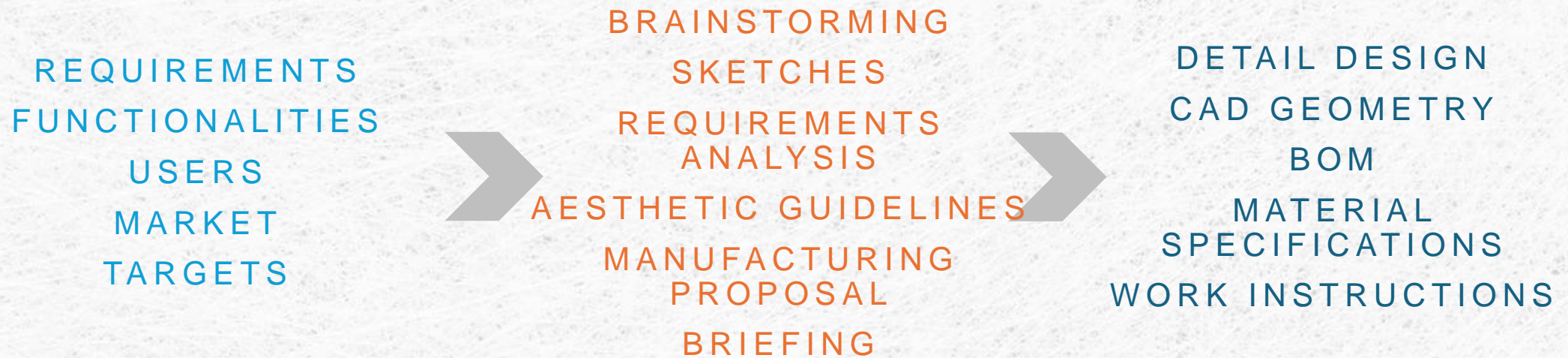
## WHAT IS CONCEPT DESIGN?

CONCEPT DESIGN IS THE PHASE BETWEEN THE IDEA AND THE PART DESIGN



## WHAT IS CONCEPT DESIGN?

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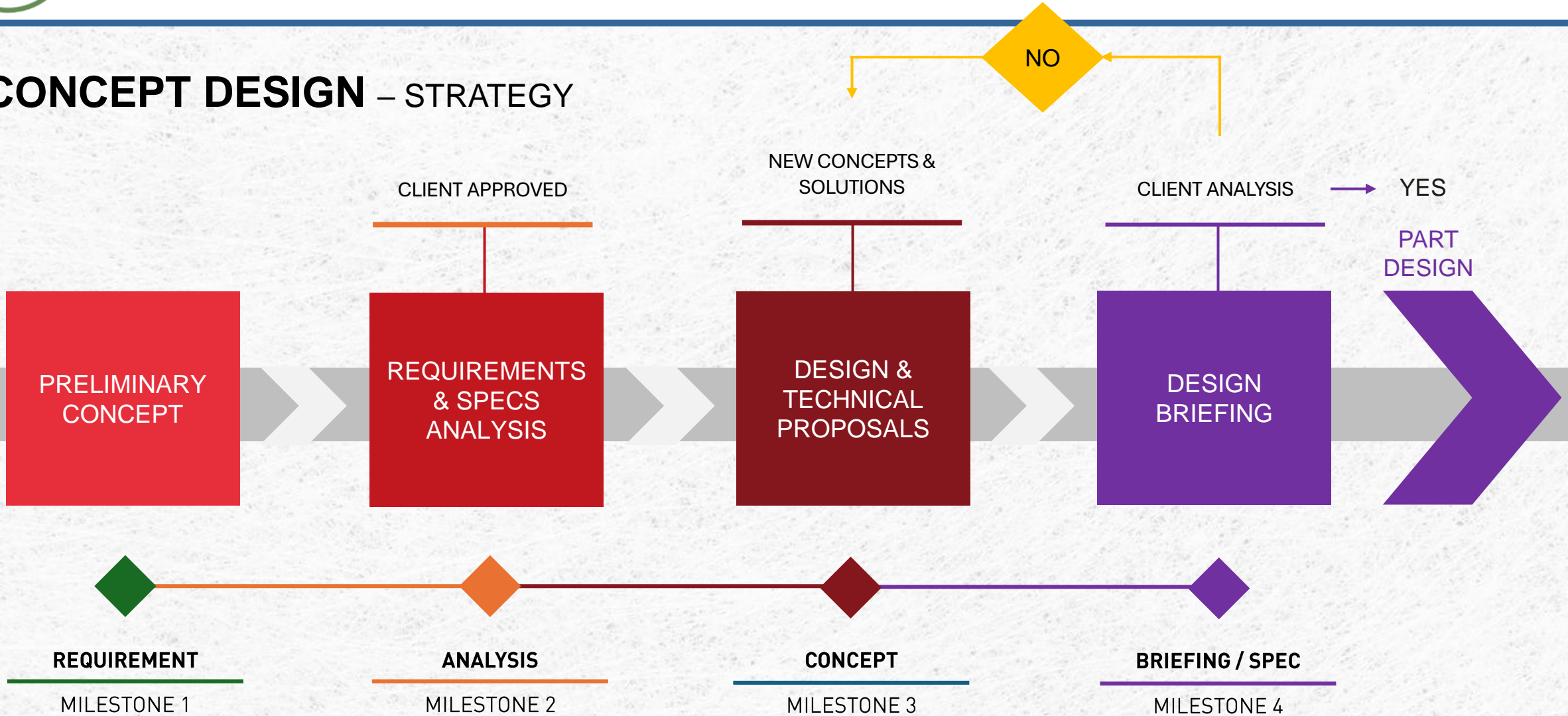
## CONCEPT DESIGN – STRATEGY

- WHO IS OUR CLIENT
- WHAT THE CLIENT WANTS TO DEVELOP
- WHICH FEATURES HAS THE PRODUCT/PART
- WHEN THE PRODUCT/PART MUST BE READY
- WHICH RESOURCES REQUIRE THIS DEVELOPMENT
- ...



**WHAT  
SHOULD  
WE DO?**

## CONCEPT DESIGN – STRATEGY



## PRELIMINARY CONCEPT

### REQUIREMENT/SPECS



MATERIAL SELECTION



DEFECTS & INSPECTION



SIZE & GEOMETRY



UNITS, COSTS & TIME



LAYUP



ASSEMBLY



INSERTS, FIXINGS &  
HARDWARE



PART LIFE



FUNCTION



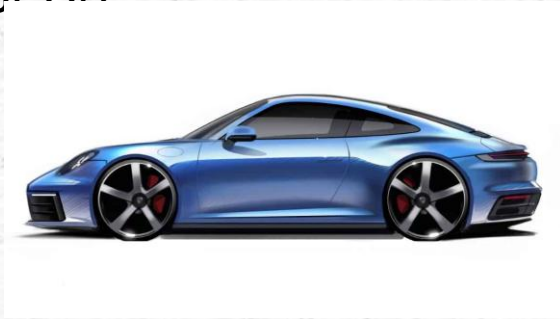
LOGISTICS



MANUFACTURING

## PRELIMINARY CONCEPT

REQUIREMENT/SPECIFICATION

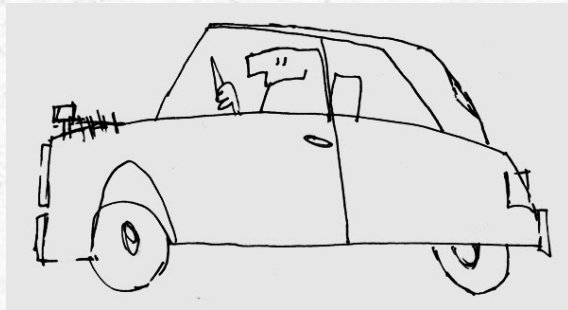


- FWD Fin for Koenigsegg
- 500 x 300 x 50 mm
- Carbon Fiber from Deltapreg
- Prepreg technology preferred
- Assembled using fasteners
- Polished finish
- 50 units per year / 500 u total
- Needed 5 months from now



**MORE  
EFFICIENT  
CONCEPT  
DESIGN**

WHAT YOU  
RECEIVE



- Fin for Hypercar
- Size undetermined
- Carbon Fiber
- The best finish possible
- Low cost
- Undetermined quantities
- Needed for yesterday



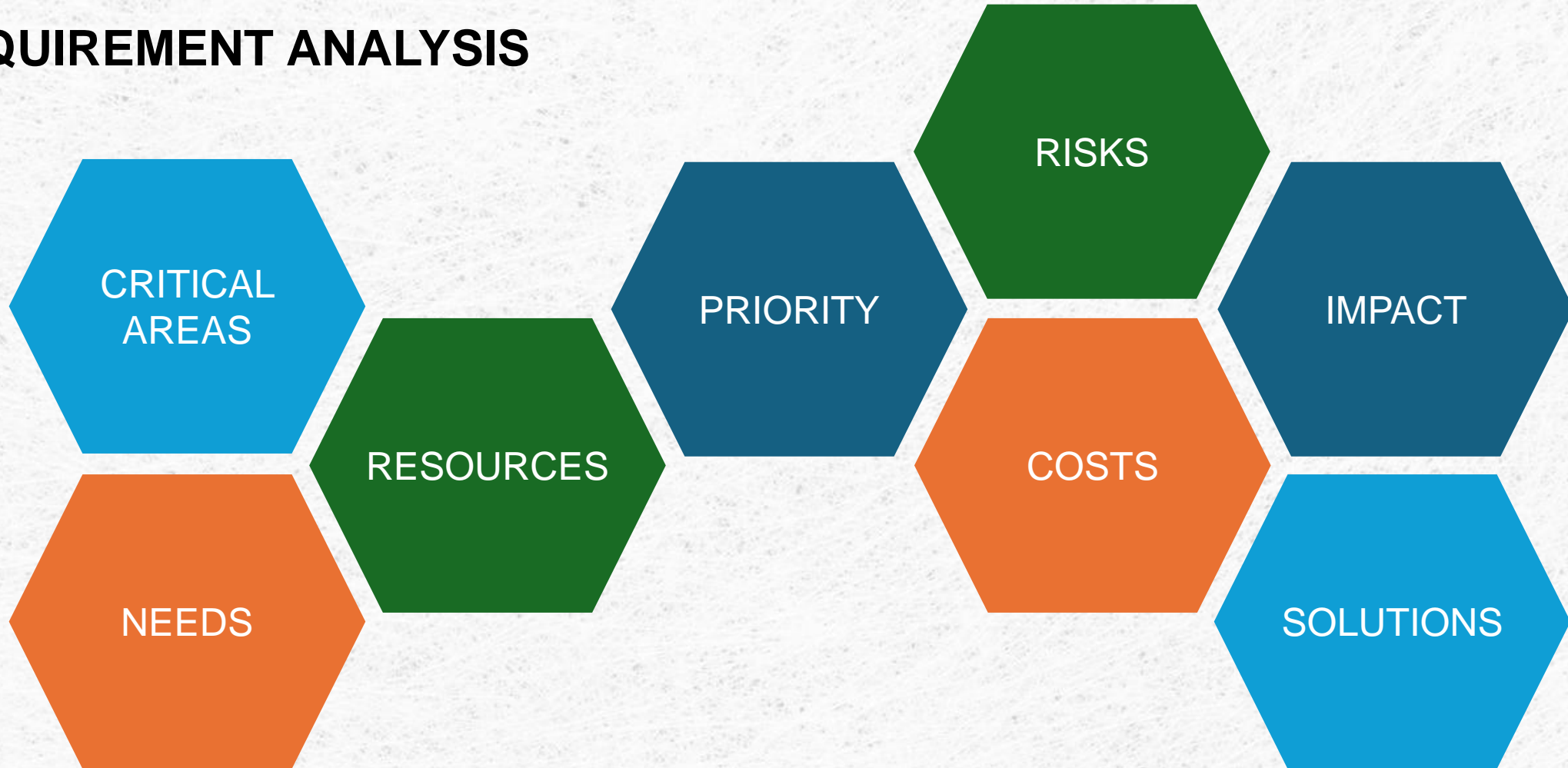
**LONGER AND  
RISKIER  
CONCEPT  
DESIGN**

## REQUIREMENT ANALYSIS

### WHERE SHOULD WE START?

- Which are the requirements?
- Which is the starting point?
- What resources are needed for developing the part/product?
- Which activities must be prioritized?
- How much will this development cost?
- Which areas affect the requirement?
- Which risks must be considered for achieving the requirements?
- ...

## REQUIREMENT ANALYSIS



## REQUIREMENT ANALYSIS

### EVALUATION MATRIX

- A
- B
- C
- D
- E
- F

REQUIREMENT	CRITICAL POINT	NEEDS	OPPORTUNITY / SOLUTION	PRIORITY	COST	RISK	RISK DESCRIPTION
				1	2	3	

## VALUE ANALYSIS

WHICH VALUE METHODS ARE USED?

- The value analysis purpose is to ensure that the cost of the part/product is not greater than is necessary to carry out its functions.

■ DAFO	→	BUSINESS STRATEGY
■ Porter	→	BUSINESS STRATEGY
■ Environment Diagram	→	PRODUCT DEVELOPMENT
■ SAFE	→	PRODUCT DEVELOPMENT
■ Cross Classification	→	<b>PRODUCT / PART ANALYSIS</b>
■ ...		

## CROSS CLASSIFICATION

WHAT IS A CROSS CLASSIFICATION?

**FUNCTIONS**



WHICH ARE  
THE MOST  
**IMPORTANT**  
FUNCTIONS?

WHICH IS THE  
**COST** OF  
THESE  
FUNCTIONS?



**SOLUTIONS  
PRIORITY  
LIST**

---

CROSS CLASSIFICATION

## CROSS CLASSIFICATION

WHAT IS A CROSS CLASSIFICATION?

1 / 2 / 3 → APPLIED TO BETTER FUNCTION

0 → APPLIED TO OPPOSITE

FUNCTIONS



	F1	F2	F3	F4	F5	F6	F7	T	%
F1		1	2	1	2	2	3	11	36.6
F2	0		1	1	2	1	2	7	23.3
F3	0	0		0	2	1	2	5	16.6
F4	0	0	1		1	0	2	3	10
F5	0	0	0	0		0	2	2	6.6
F6	0	0	0	1	1		2	2	6.6
F7	0	0	0	0	0	0		0	0
								30	100



SOLUTIONS  
PRIORITY LIST

CROSS CLASSIFICATION

## CROSS CLASSIFICATION

### FUNCTIONS

- |                                 |                             |
|---------------------------------|-----------------------------|
| 1. Transport objects            | 9. Be customizable          |
| 2. Be lightweight               | 10. Be ergonomic            |
| 3. Be visually attractive       | 11. Have a safety system    |
| 4. Resist impacts               | 12. TSA homologation        |
| 5. Resist environmental factors | 13. Be comfortable          |
| 6. Good internal distribution   | 14. Adjustable to user size |
| 7. Protect interior objects     |                             |
| 8. Charge electronic devices    |                             |

### IMPORTANCE

	F1	F2	F3	F4	F5	F6	F7	T	%
F1		1	2	1	2	2	1	11	36.6
F2	0		1	1	2	1	1	7	23.3
F3	0	0		0	2	1	0	5	16.6
F4	0	0	1		1	0	0	3	10
F5	0	0	0	0		0	0	2	6.6
F6	0	0	0	1	1		0	2	6.6
F7	0	0	2	1	2	3		0	0
								30	100

### COST

	F1	F2	F3	F4	F5	F6	F7	T	%
F1		0	0	0	1	1	0	2	5.8
F2	3		2	1	3	3	1	13	38.2
F3	2	0		0	2	2	0	6	17.6
F4	1	0	1		2	2	1	7	20.6
F5	0	0	0	0		1	0	1	3
F6	0	0	0	0	0		0	0	0
F7	1	0	1	0	1	2		5	14.7
								34	100

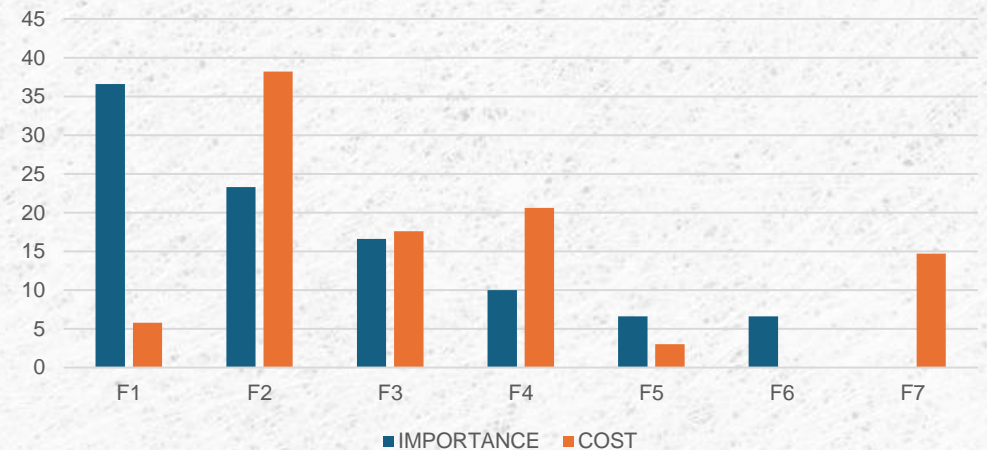
## CROSS CLASSIFICATION

### FUNCTIONS

- |                                 |                             |
|---------------------------------|-----------------------------|
| 1. Transport objects            | 9. Be customizable          |
| 2. Be lightweight               | 10. Be ergonomic            |
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| 6. Good internal distribution   | 14. Adjustable to user size |
| 7. Protect interior objects     |                             |
| 8. Charge electronic devices    |                             |

	IMPORTANCE %	COST %	IMPORTANCE / COST
F1	36.6	5.8	6.3
F2	23.3	38.2	0.6
F3	16.6	17.6	0.9
F4	10	20.6	0.5
F5	6.6	3	2.2
F6	6.6	0	N/A +
F7	0	14.7	N/A -

CROSS CLASSIFICATION



## CONCEPT DESIGN

### HOW TO DEVELOP A CONCEPT PROPOSAL

- Which is the purpose of a concept proposal?
- Which fields must be considered?
- What do we want to show and explain?
- How are we going to display the information?
- Which is the best format?
- Until which point the concept must be develop?
- Who must be involved in the concept proposal?
- ...

## VISUAL SUPPORT

### WHY WE NEED VISUAL SUPPORT

- All concept proposals are ideas that must be developed afterwards, so there is no information that shows how the solution will be aside from the concept itself.
- Sight is a very important sense in human life, and visualizing a concept helps to understand it better, so providing a visual support to the concept design of a part makes the development more efficient.

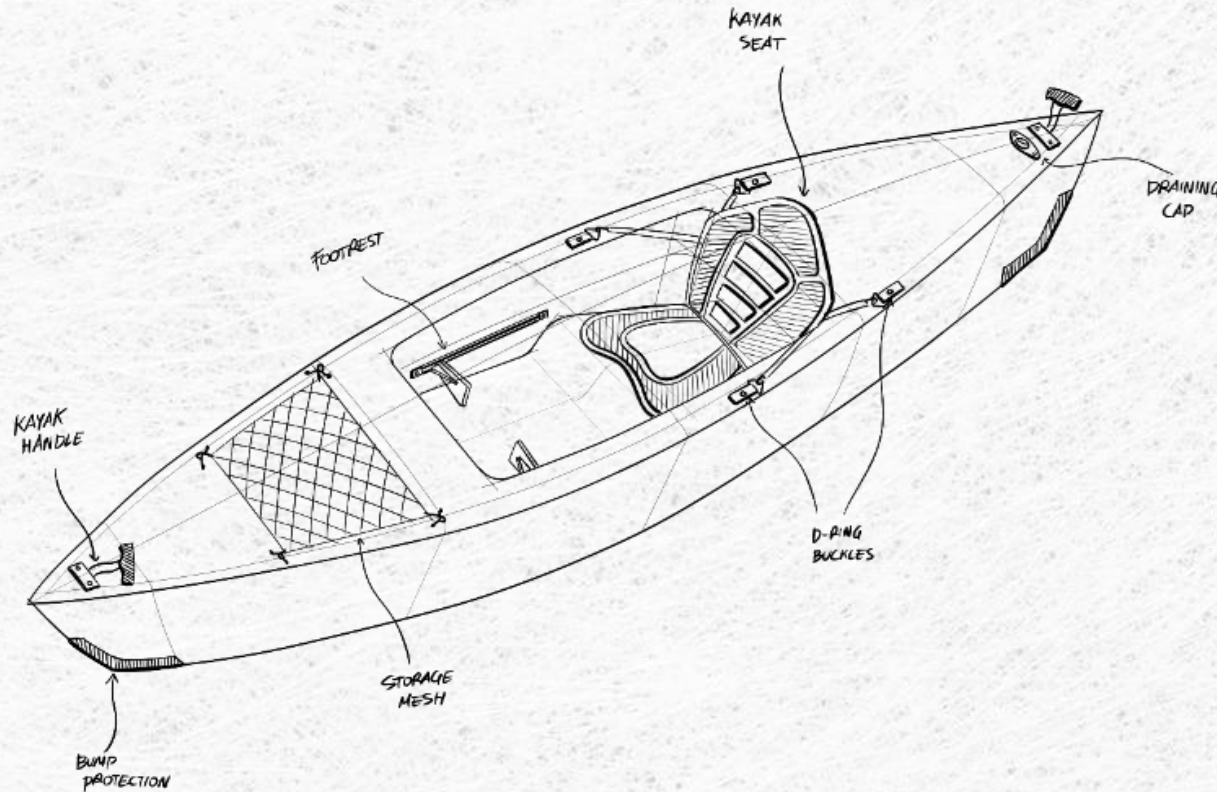
### VISUAL SUPPORT EXAMPLES

- Sketches
- CADS
- Renders
- Infographics
- Sections
- Silhouettes

## VISUAL SUPPORT

### KAYAK EXAMPLE

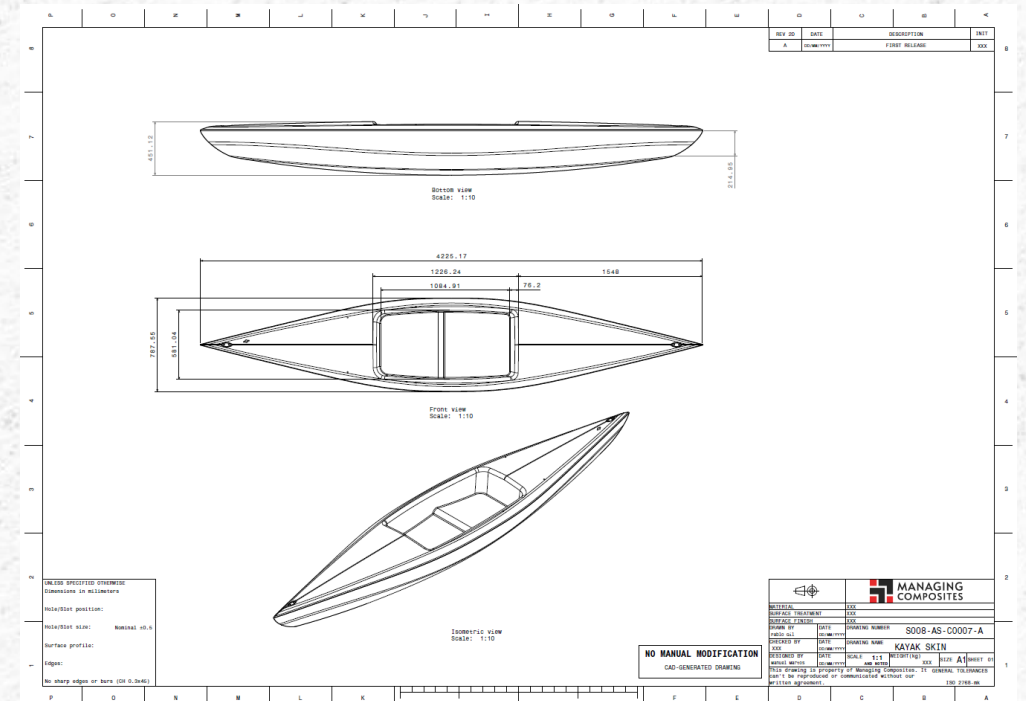
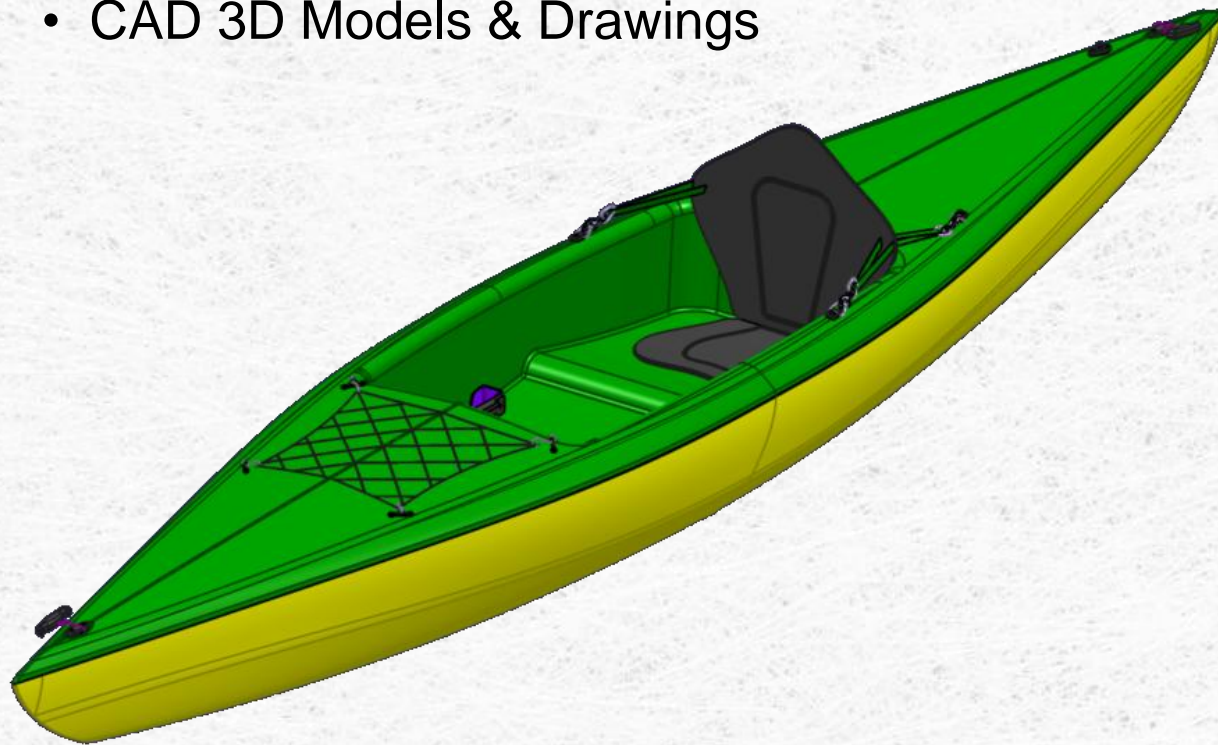
- Sketch



## VISUAL SUPPORT

### KAYAK EXAMPLE

- CAD 3D Models & Drawings



## VISUAL SUPPORT

### KAYAK EXAMPLE

- Infographics

**TECHNICAL DATA SHEET**  
**KAYAK**

**MC4**

MULTI-LEVEL CIRCULAR PROCESS CHAIN FOR CARBON AND GLASS FIBRE COMPOSITES

**PRODUCT CATEGORY:**  
SPORTING GOOD

**PRODUCT OVERVIEW**  
Fully functional Kayak and Paddle

Sit-on top hybrid Kayak manufactured through an infusion process with Glass Fiber and 3R Resin developed for recyclability.

**KEY FEATURES:** Kayak Deck, Kayak Hull, Paddle

**RECYCLE**

**KEY CHARACTERISTICS**

- Reinforcement system developed by CIDETEC is made of 3 different elements
- Glass Fiber used as a reinforcement in the composite material is a biaxial fabric of 360gsm developed by Chomarat
- Cutouts of the paddle are first cut from a 'Kayak' who's life has ended and then cut to properties of the 3R Resin, the cutouts are reshaped through a forming process.
- Reshaped blades into the Carbon Fiber Rod and reinforce the weak interface, a block of glass fiber and epoxy composite will be machined and joined between
- Carbon fiber rod is used as connection between the two blades due to its strength and excellent mechanical properties

**At first, the focus was put on the development of a new resin complying with the specifications of the envisioned manufacturing process (infusion). In a second step, a study was performed at the glass fiber level with the help of Chomarat, to select the most adequate fiber sizing to be used in combination with 3R resin. Then, the 3R composite laminates were manufactured by combining 3R resin and glass fiber fabrics and used for mechanical characterization and demonstrators' designs validation. Finally, thermofforming trials were carried out on these 3R composite laminates to explore the limitations of the process and define a processing window for the recycling of kayak parts into paddles.**

data expressed are however those of those of the European Union or the Member States of the European Union nor the Commission.

## VISUAL SUPPORT







### KAYAK EXAMPLE

- Renders



## BRIEFING

### HOW TO GATHER EVERYTHING

-  GENERAL DESCRIPTION OF PART / PRODUCT
-  GEOMETRICAL SPECIFICATIONS
-  AESTHETIC LOOK
-  MATERIALS & TECHNOLOGY SELECTED
-  PRELIMINARY COSTS DISTRIBUTION
-  ELEMENTS INVOLVED



# BRIEFING

## BRIEFING

MUST BE ADAPTED TO EACH CASE/SCENARIO



**DESCRIPTION TABLE**



**CHECKLIST**



**FORMAL DOCUMENT**

## BRIEFING

### WHAT SHOULD BE INCLUDED?

The Briefing can include as much information as it is needed, but a few points are recommended as a standard base:

- BOM
- Sketches & Visual support
- Description of features
- Manufacturing proposal
- Business case
- ...

## WHAT IS CONCEPT DESIGN?

BRIEFING

BRAINSTORMING

SKETCHES

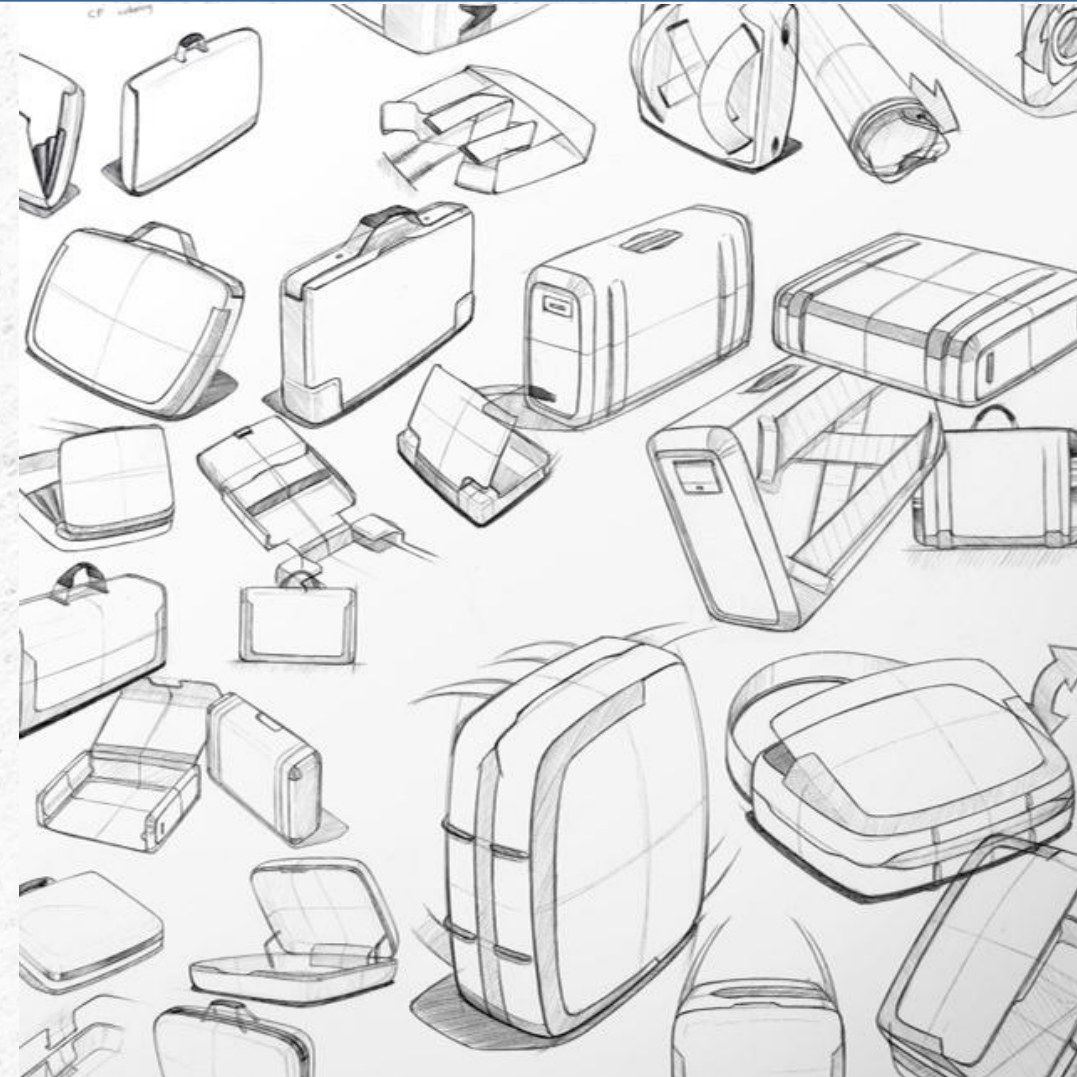
RESEARCH

REQUIREMENTS

BASIC GEOMETRY

ANALYSIS

CONCEPT  
PROPOSALS



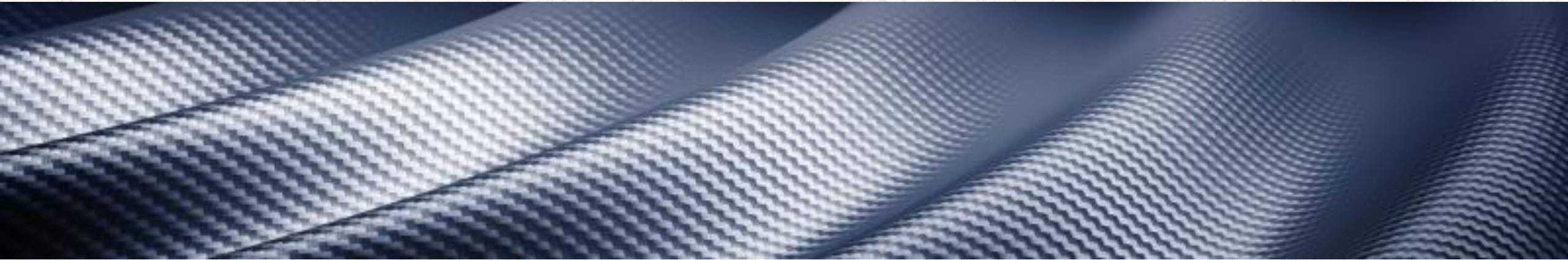
## PART DESIGN

WHAT SHOULD BE CONSIDERED?

- Fiber Continuity
- Joint Locations
- B-Surfaces
- Mould & Master
- Overlaps

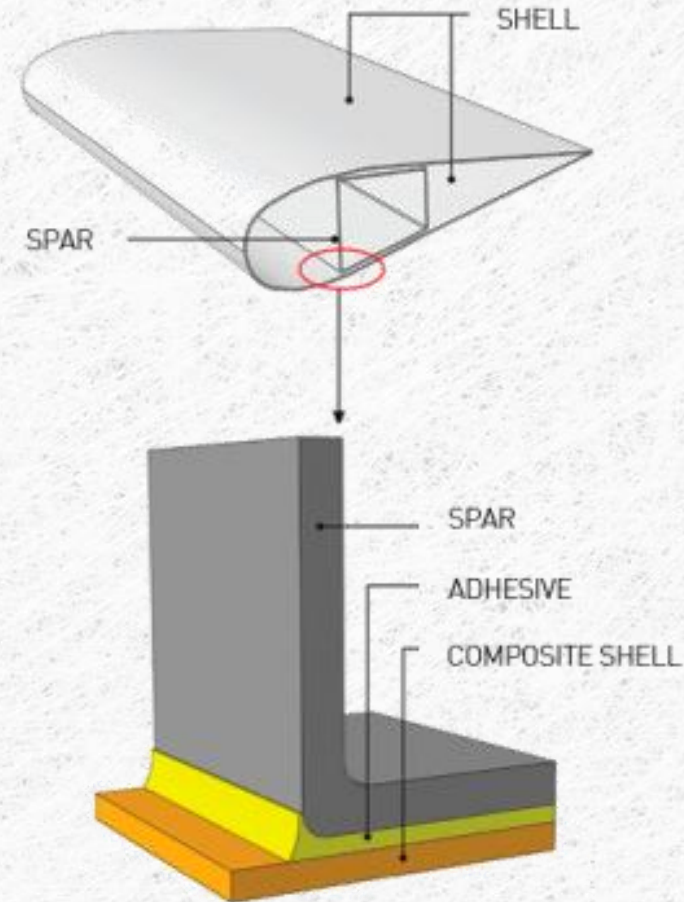
## PART DESIGN

FIBER CONTINUITY



## PART DESIGN

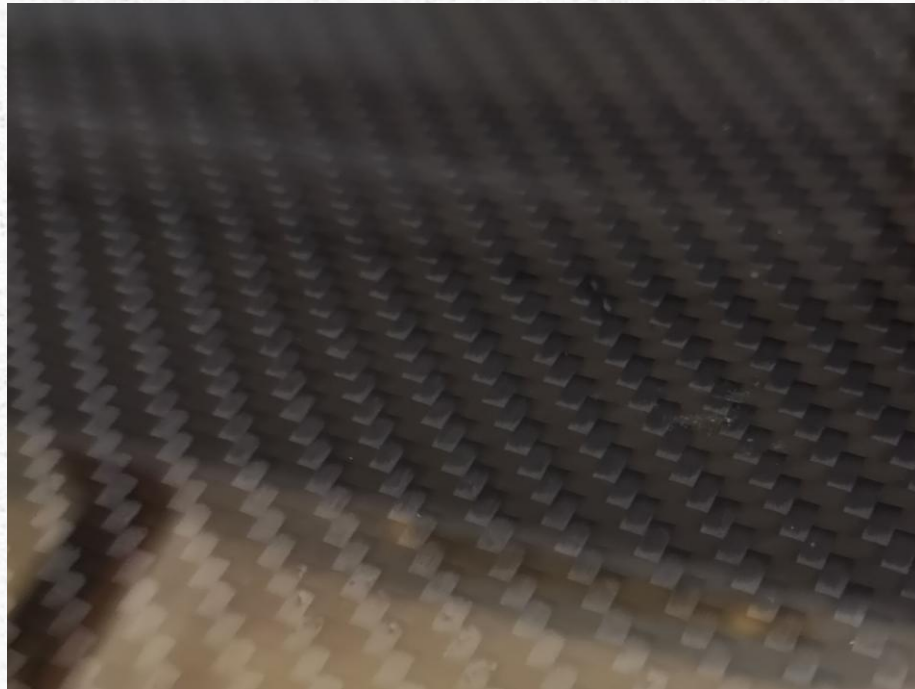
### JOINT LOCATIONS



## PART DESIGN

### B-SURFACES

A



B



## PART DESIGN

### MOULDS & MASTERS

Access to laminate



## PART DESIGN

### OVERLAPS



## JOINTS & INTERFACES

### TYPES

#### MECHANICAL JOINTS



#### ADHESIVE JOINTS



## JOINTS & INTERFACES

### TYPES

#### MECHANICAL JOINTS



#### ADHESIVE JOINTS



## JOINTS & INTERFACES

TYPES

### MECHANICAL JOINTS







SIMPLER

CLEANER

TIGHTENING TORQUE

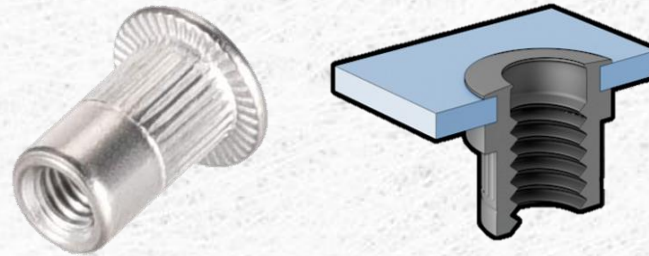
NOT PERMANENT

## MECHANICAL JOINTS

-  RIVET NUTS
-  BIGHEADS
-  NUTPLATES
-  THREADED INSERTS
-  FLOATING NUTS
-  MOLDED BLOCK

## INTERFACES & INSERTS







TYPES



APPLICATION



## MECHANICAL JOINTS

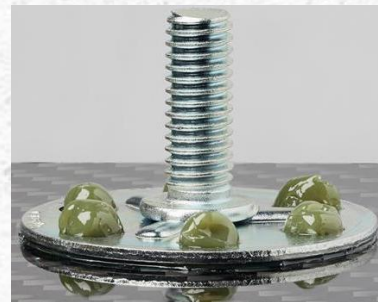
-  RIVET NUTS
-  BIGHEADS
-  NUTPLATES
-  THREADED INSERTS
-  FLOATING NUTS
-  MOLDED BLOCK

## INTERFACES & INSERTS







### TYPES



### APPLICATION



## MECHANICAL JOINTS

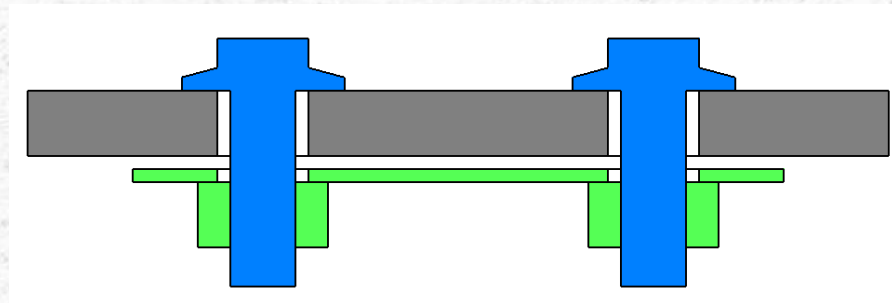
-  RIVET NUTS
-  BIGHEADS
-  NUTPLATES
-  THREADED INSERTS
-  FLOATING NUTS
-  MOLDED BLOCK

## INTERFACES & INSERTS







TYPES



APPLICATION



## MECHANICAL JOINTS

-  RIVET NUTS
-  BIGHEADS
-  NUTPLATES
-  **THREADED INSERTS**
-  FLOATING NUTS
-  MOLDED BLOCK

## INTERFACES & INSERTS







### TYPES



### APPLICATION



## MECHANICAL JOINTS

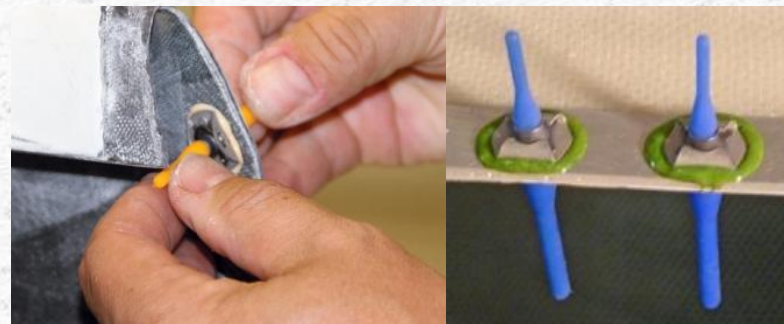
-  RIVET NUTS
-  BIGHEADS
-  NUTPLATES
-  THREADED INSERTS
-  FLOATING NUTS
-  MOLDED BLOCK

## INTERFACES & INSERTS







### TYPES



### APPLICATION

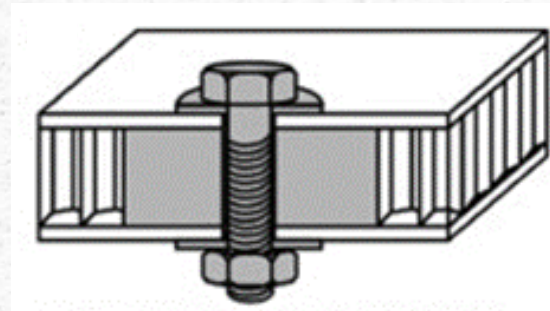


## MECHANICAL JOINTS

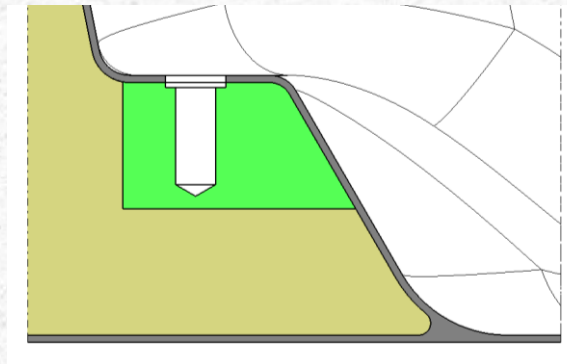
-  RIVET NUTS
-  BIGHEADS
-  NUTPLATES
-  THREADED INSERTS
-  FLOATING NUTS
-  MOLDED BLOCK

## INTERFACES & INSERTS

TYPES



APPLICATION



## JOINTS & INTERFACES

### TYPES

#### MECHANICAL JOINTS



#### ADHESIVE JOINTS



## JOINTS & INTERFACES

### TYPES

## ADHESIVE JOINTS

UNIFORM LOAD  
DISTRIBUTION

SEAL FROM  
ENVIRONMENT

AESTHETICS

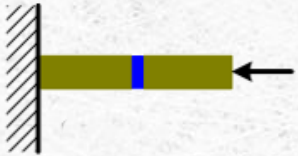
WEIGHT REDUCTION

NO HOLES

ABSORB  
TOLERANCES

## JOINTS & INTERFACES

### ADHESIVE JOINTS



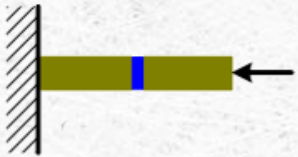
## JOINTS & INTERFACES

### ADHESIVE JOINTS



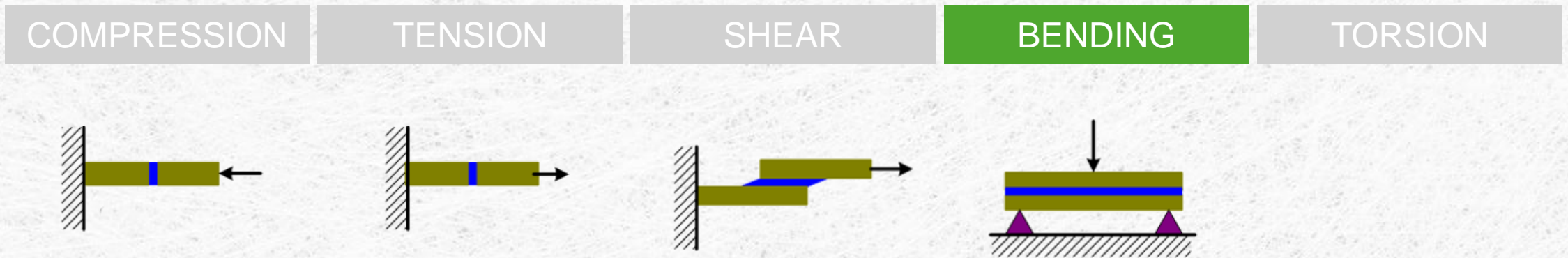
## JOINTS & INTERFACES

### ADHESIVE JOINTS



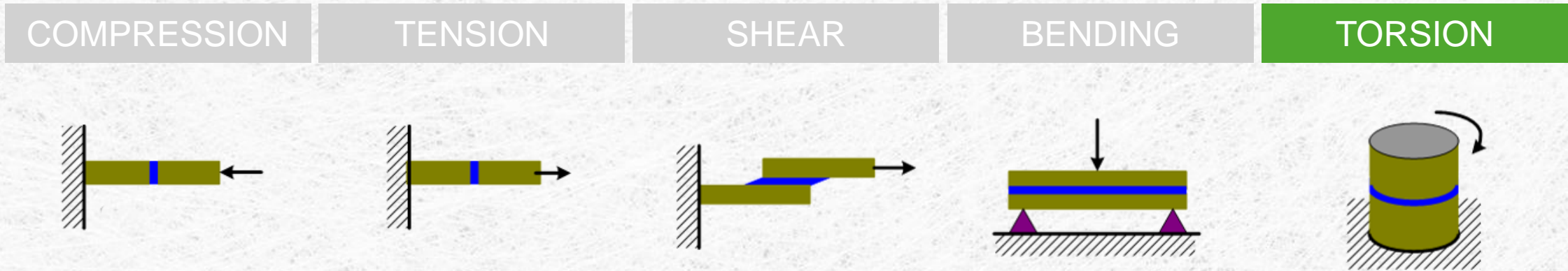
## JOINTS & INTERFACES

### ADHESIVE JOINTS



## JOINTS & INTERFACES

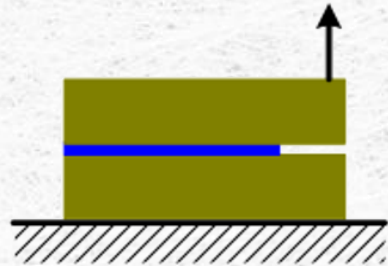
### ADHESIVE JOINTS



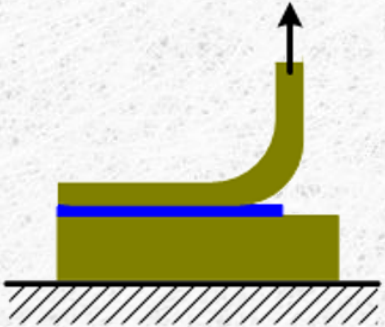
## JOINTS & INTERFACES

ADHESIVE JOINTS – UNDESIRABLE LOADING

**CLEAVAGE**  
(RIGID SUBSTRATES)

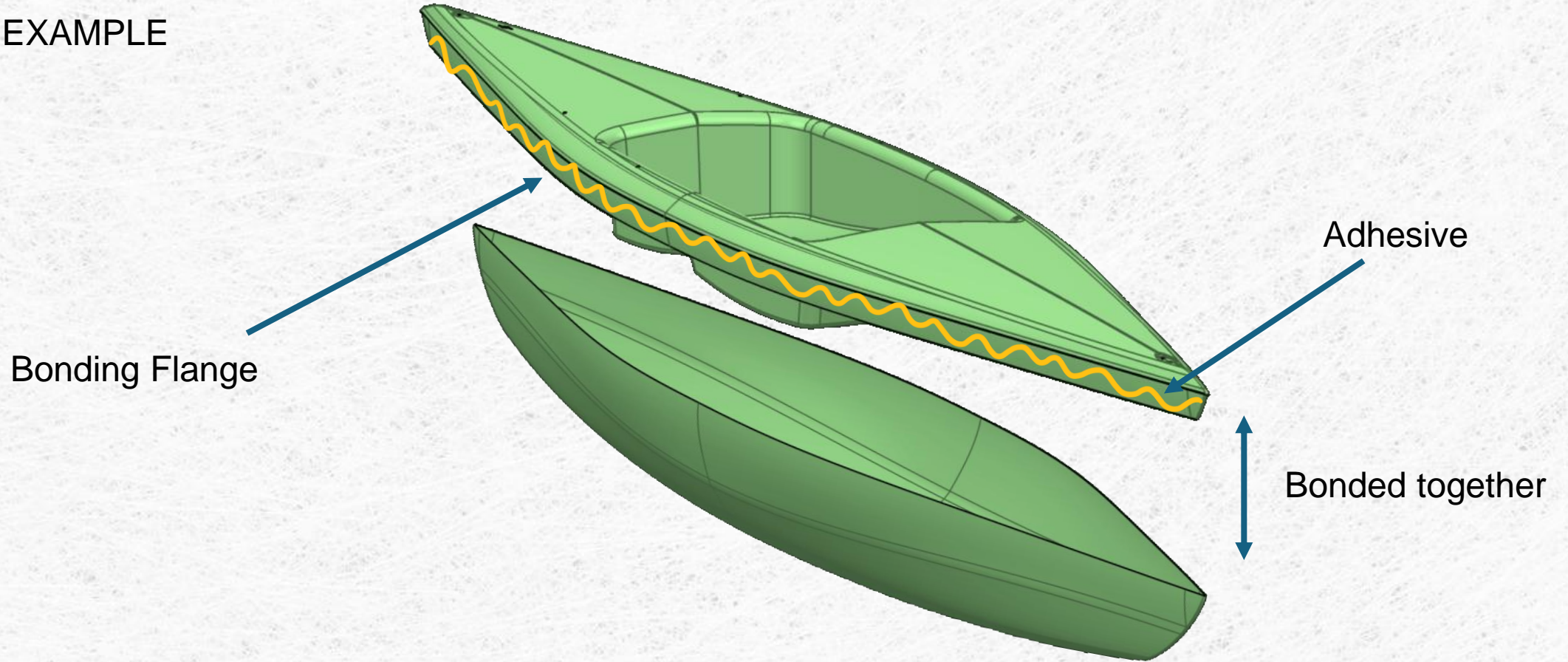


**PEEL**  
(ELASTIC SUBSTRATES)



## JOINTS & INTERFACES

KAYAK EXAMPLE



## LAYUP & DFM

### THINGS TO CONSIDER

HOLES

SYMMETRIC  
LAMINATE

LAST FABRIC  
LAYER

CONSECUTIVE  
LAYERS

CURING PROCESS

STRIPE DIRECTION

OVERLAP  
DISTANCE

PROGRESSIVE  
OVERLAPS

VISUAL IMPACT

MATERIAL  
QUANTITY

CORE INTERFACE  
& CHAMFER

## LAYUP & DFM

DFM PRINCIPLES



## LAYUP & DFM

### DFM BENEFITS

IDENTIFY AND REDUCE ERRORS

REDUCES PRODUCTION COST

CREATES SAFE WORK ENVIRONMENT

ALLOWS TO IMPROVE DESIGN

SHORTER DEVELOPMENT PROCESS

## LAYUP & DFM

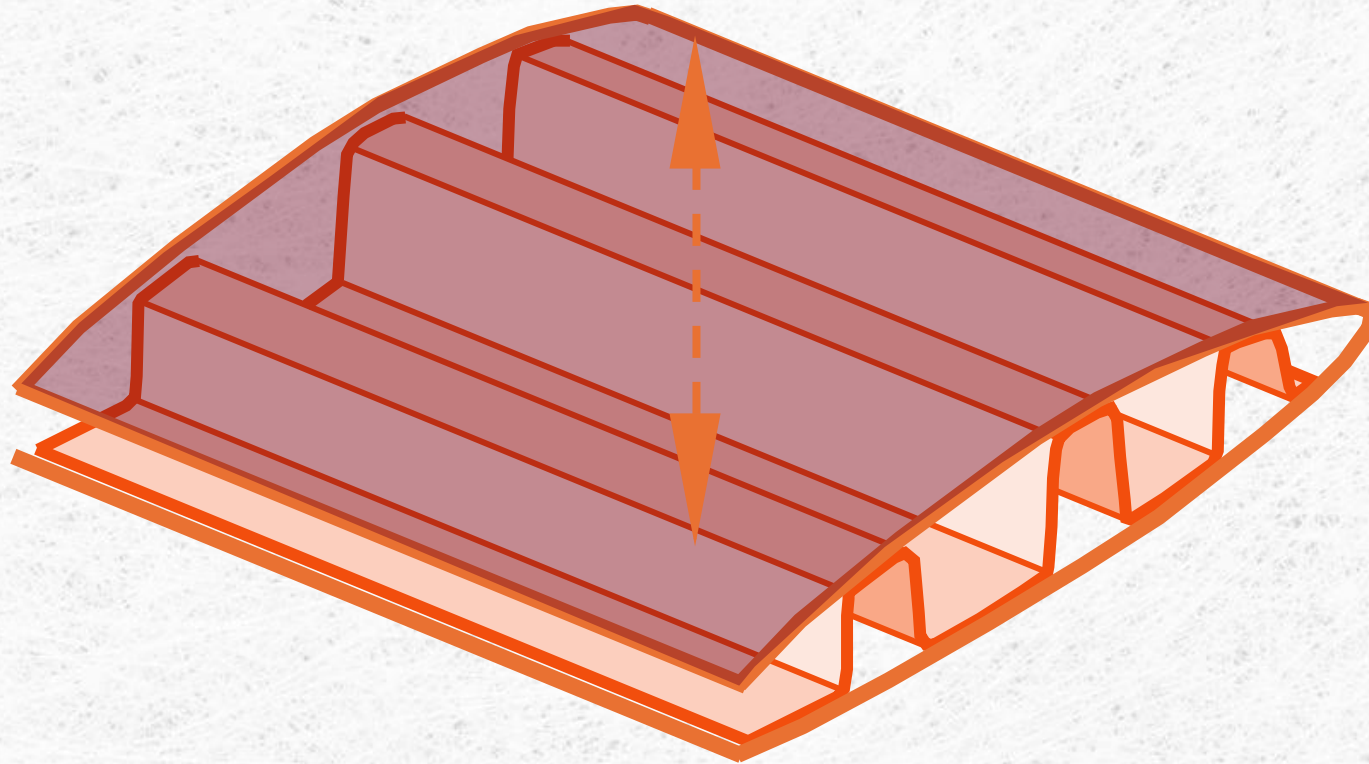
### POKA-YOKE

This method avoids having a wrong way of placing or using something as shown in the following examples:



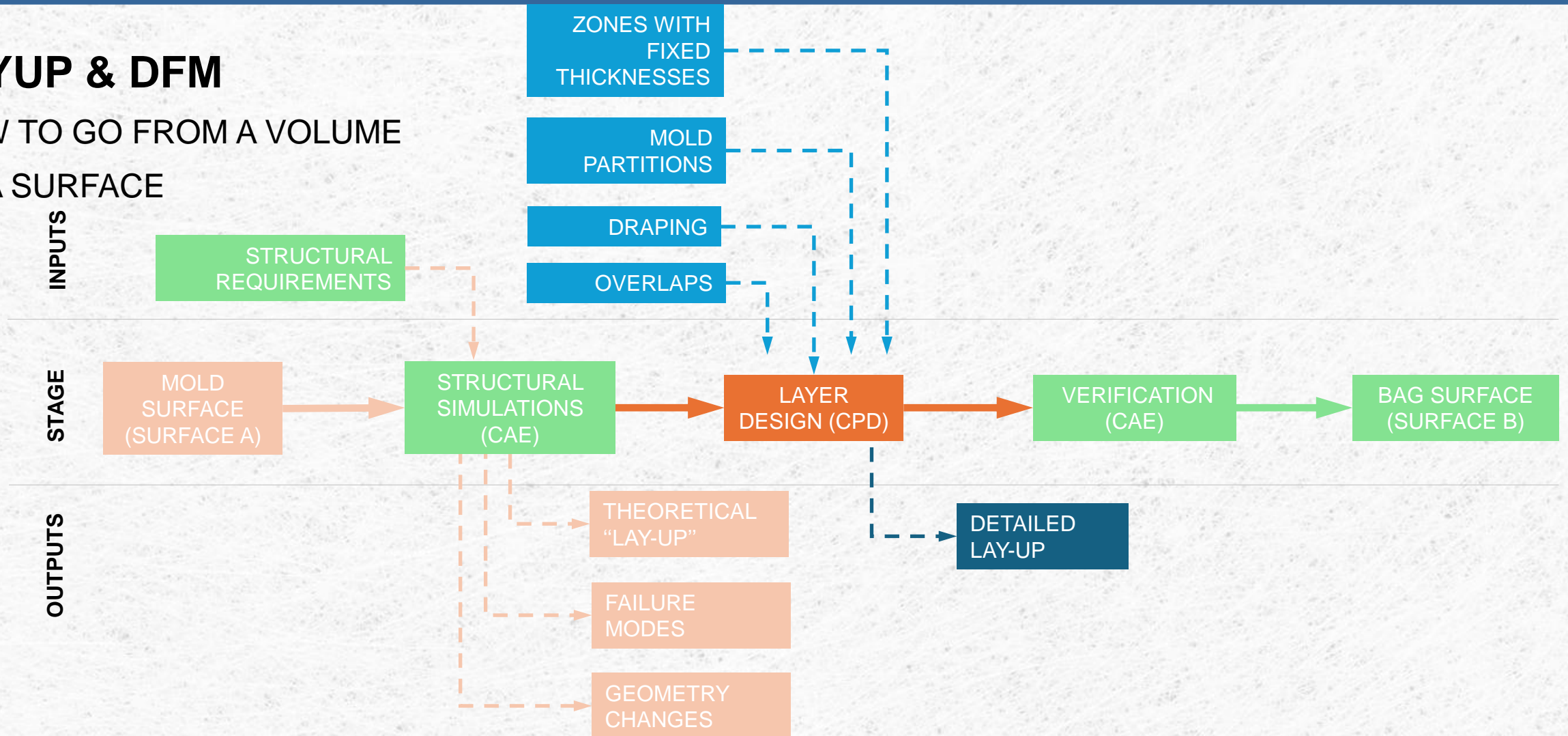
## LAYUP & DFM

POKA-YOKE

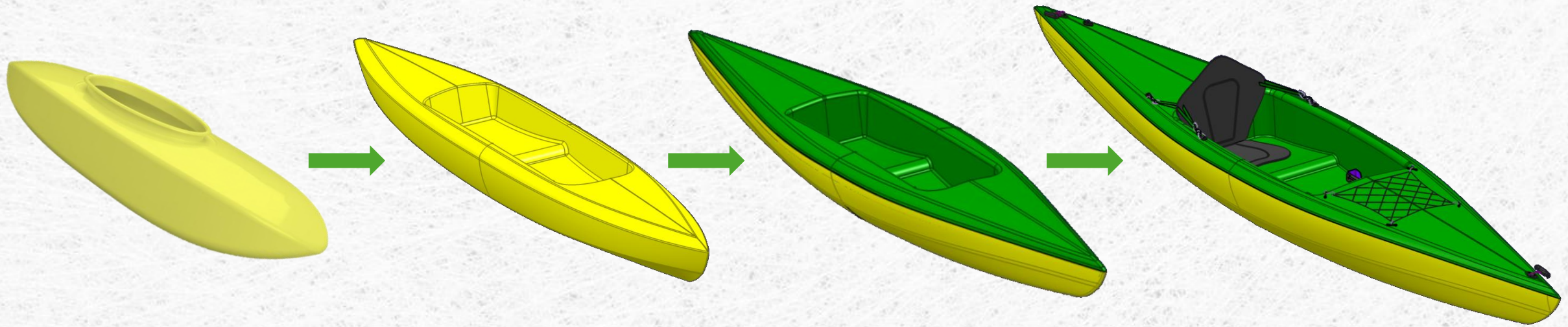


## LAYUP & DFM

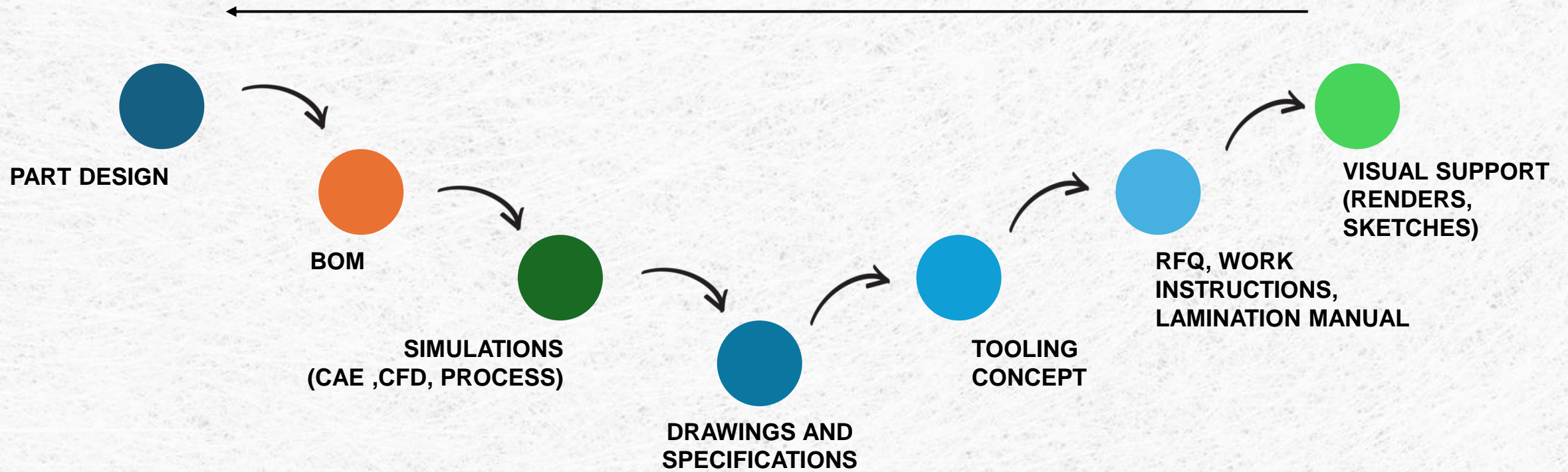
HOW TO GO FROM A VOLUME TO A SURFACE



## DESIGN ITERATIONS



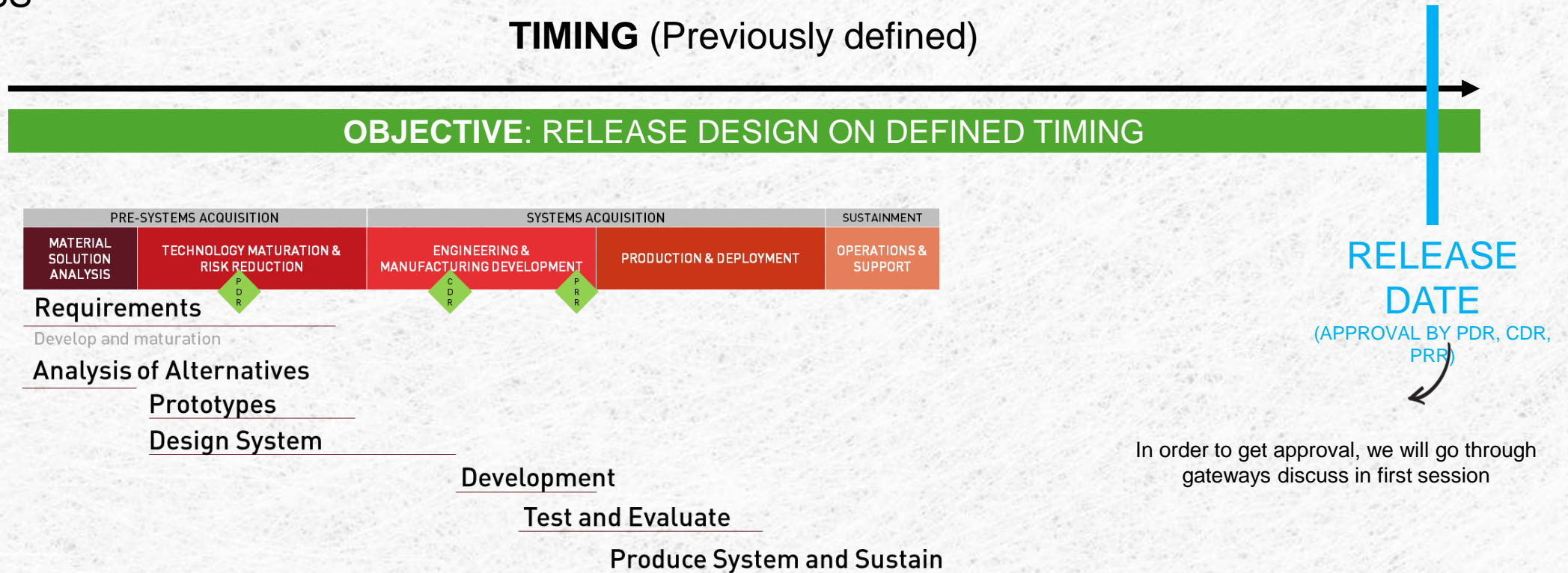
## DESIGN ITERATIONS



## DESIGN ITERATIONS

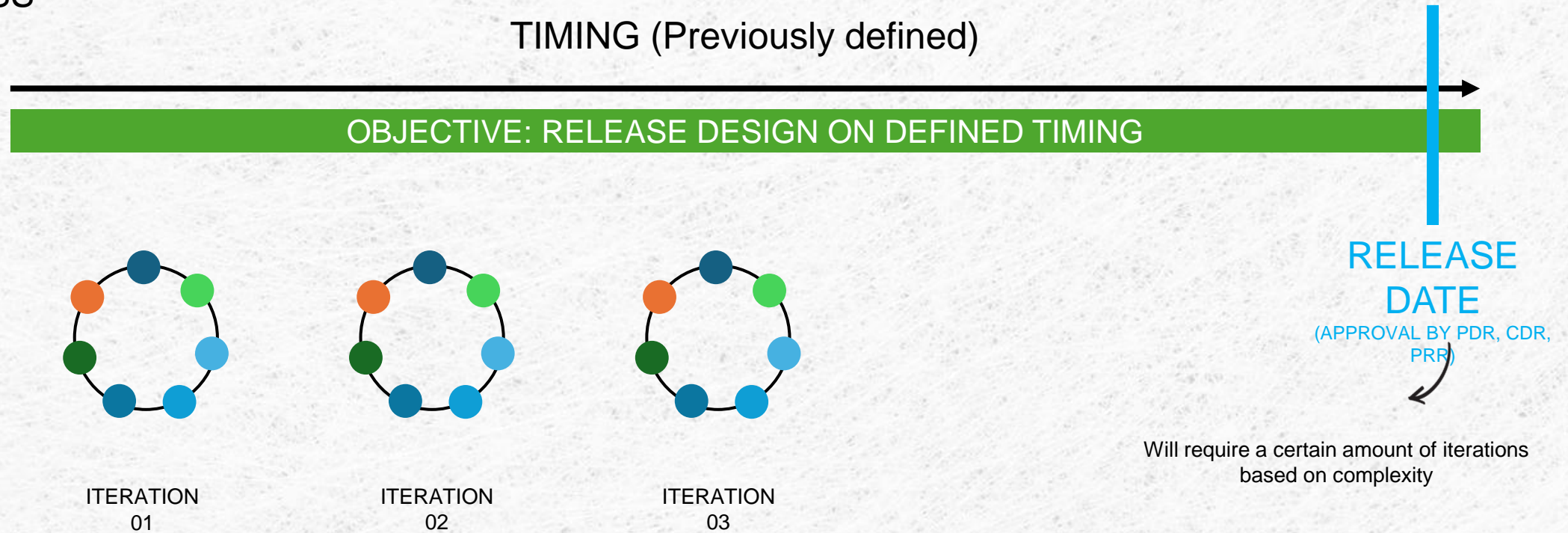
### PROCESS

**TIMING** (Previously defined)



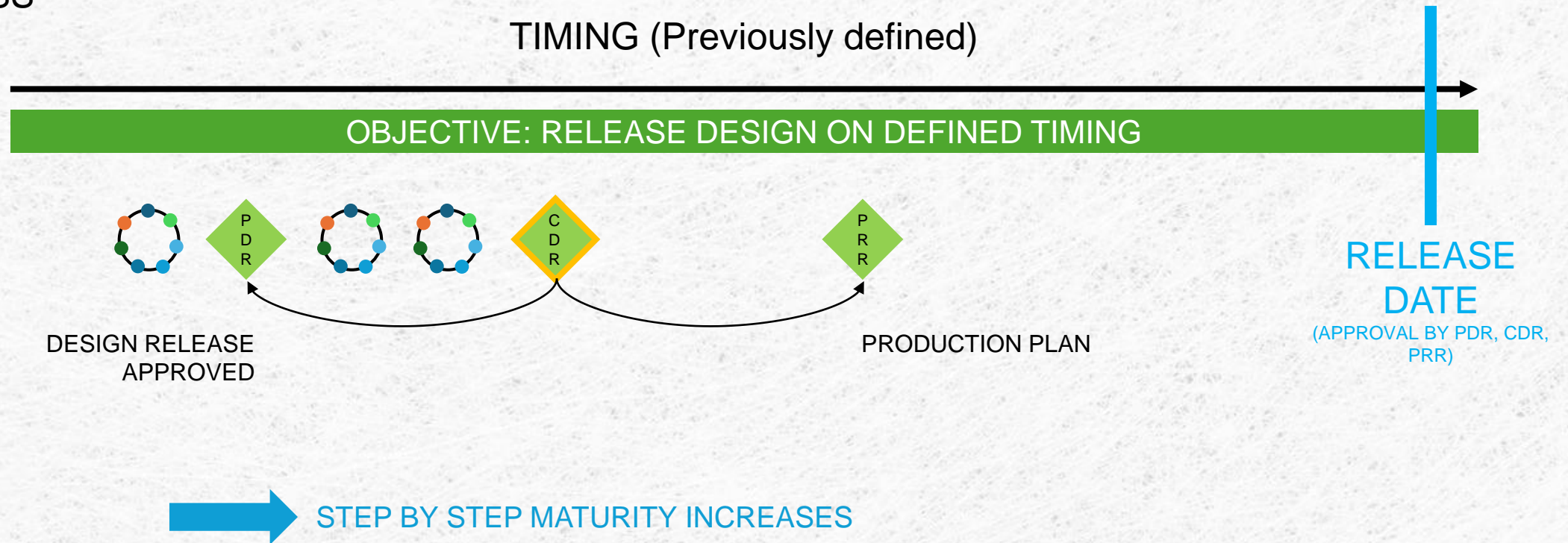
## DESIGN ITERATIONS

### PROCESS



## DESIGN ITERATIONS

PROCESS



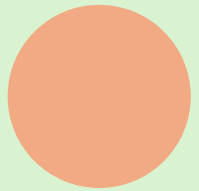
## DESIGN ITERATIONS

### PROCESS



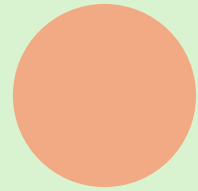
## DESIGN ITERATIONS

### PROCESS



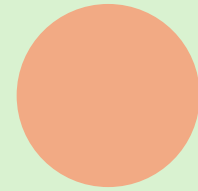
#### HYDRODYNAMICS

- FLOATABILITY TARGET
- HYDRODYNAMIC PERFORMANCE



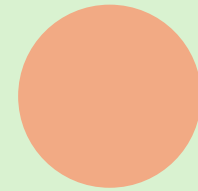
#### MECHANICAL DESIGN

- DETAIL DESIGN WITH TOLERANCES AND MANUFACTURABLE



#### HARDWARE

- POSITIONING
- INTERFACES
- ETC.

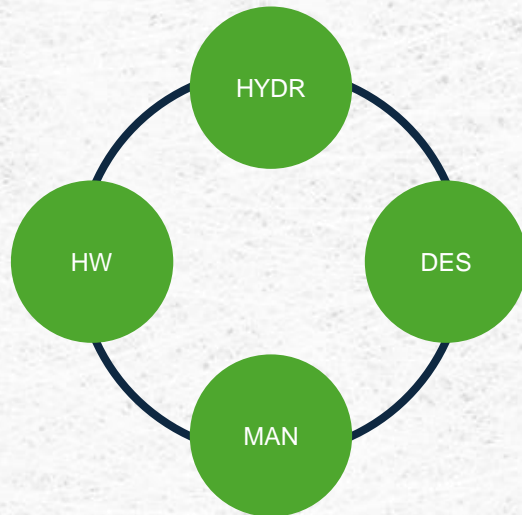


#### MANUFACTURING

- ASSEMBLY FINAL PRODUCT

## DESIGN ITERATIONS

### PROCESS



WILL GENERATE OUTPUTS  
(THAT MIGHT CLASH OR WON'T MATCH THE TARGET/EXPECTATIONS)

# Contact and acknowledgements



Funded by  
the European Union



Multi-level Circular  
Process Chain for Carbon  
and Glass Fibre Composites

### Website

<https://www.mc4-project.eu>



### LinkedIn

<https://www.linkedin.com/company/mc4-project>



### E-mail

[Christian.Eitzinger@profactor.at](mailto:Christian.Eitzinger@profactor.at)



The partners of MC4 are:

**Profactor** (Austria, coordinator)

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**GAIKER** (Spain)

**CIDETEC** (Spain)

**STFI** (Germany)

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**VDL Fibertech Industries** (The Netherlands)

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MC4 is entirely funded by the European Union, under the topic HORIZON-CL4-2021-RESILIENCE-01-01 of the Horizon Europe Framework Programme (HORIZON).

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**Thank you for your attention**

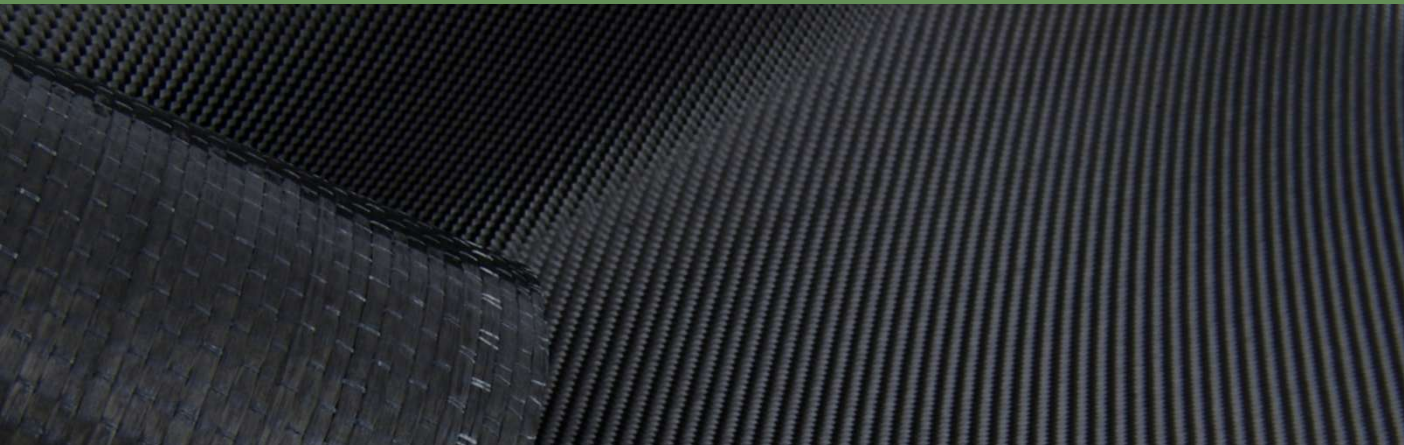


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**Multi-level Circular  
Process Chain for Carbon  
and Glass Fibre Composites**

# ANNEX B



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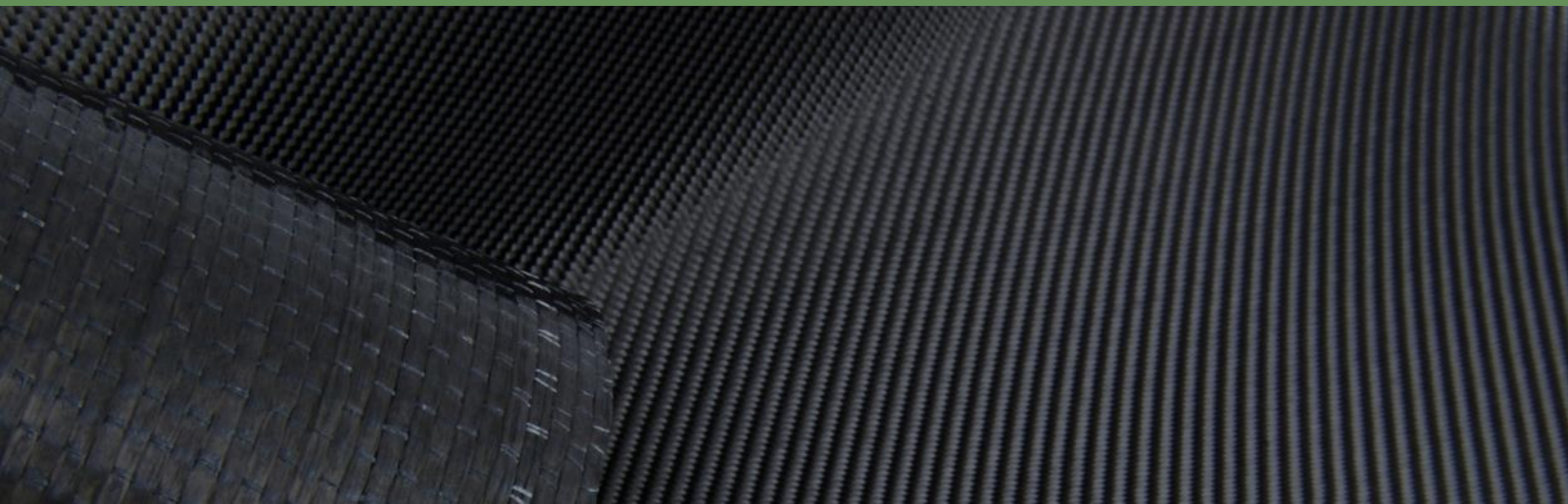
**Multi-level Circular  
Process Chain for Carbon  
and Glass Fibre Composites**

# **Educational material for process and product engineers: CAE methodology**

07/02/2025



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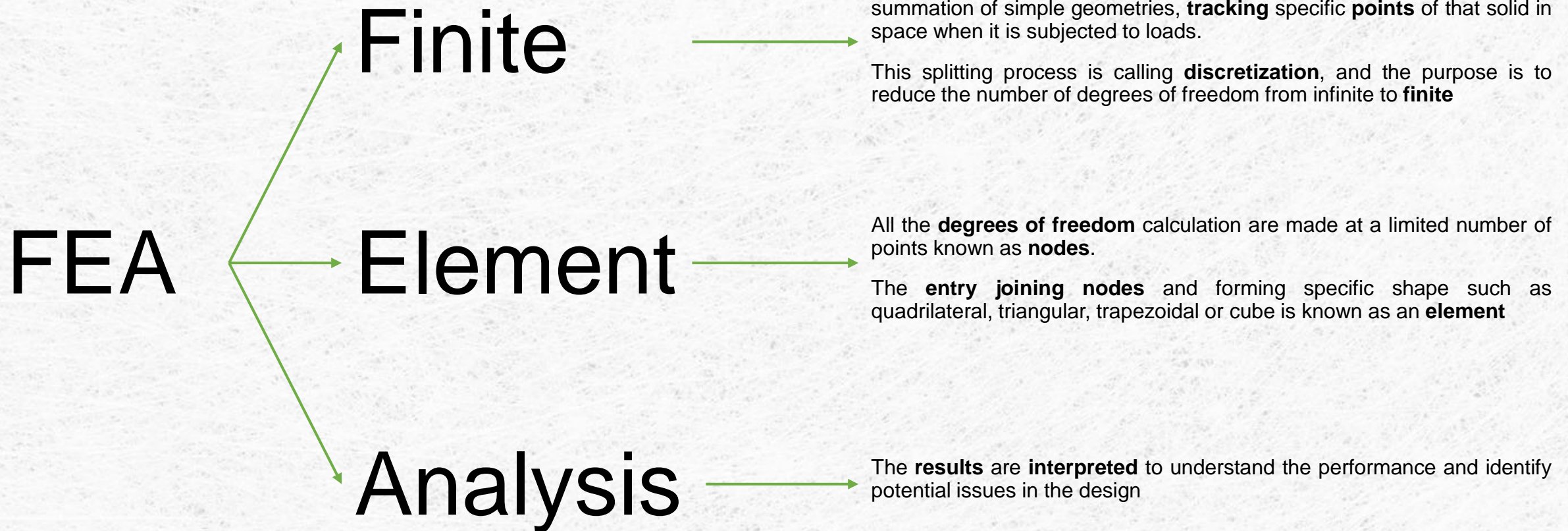
- Introduction
- Fundamentals of FEA
- Fundamentals of CFD
- Structural simulations
  - Common sub-steps
  - Material definition
  - Properties definition
  - Material reference orientation
  - Laminate definition
  - Lamination theory checks
- Process simulation
  - Liquid composite modeling
  - Flow in porous medium

The aim of this document is to teach the basics about how FEA (Finite Element Analysis) and CFD (Computational Fluid Dynamics) are applied during the dimensioning of products made up of recycled or recyclable composite materials

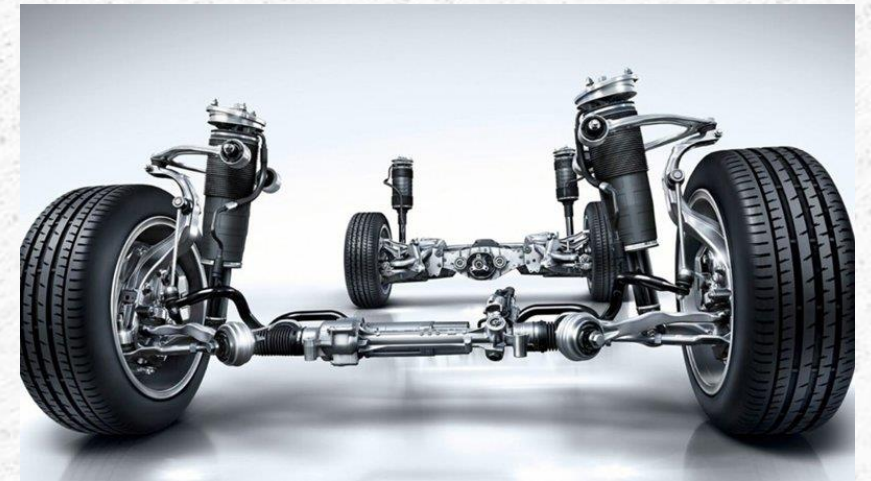
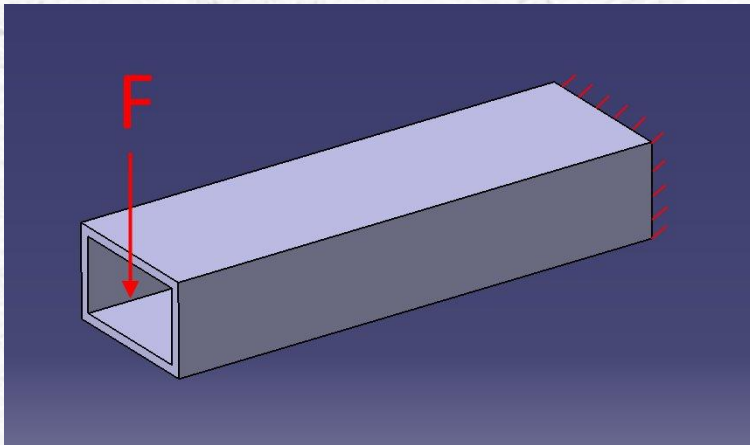
# Fundamentals of FEA



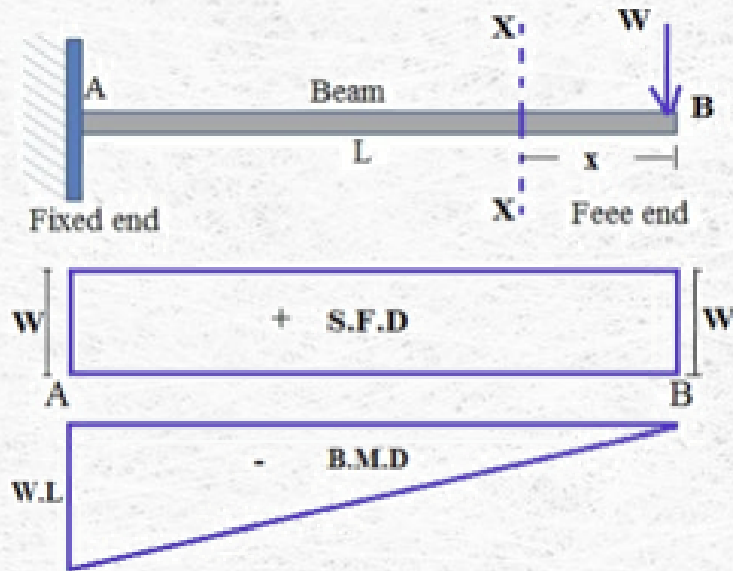
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Deformable solids examples:

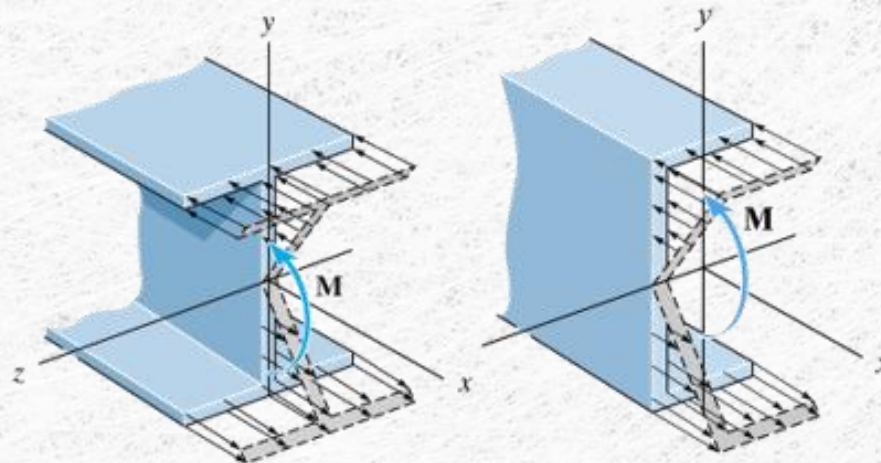


## Previous structural analysis approaches



Limited to simple geometries!

### Stress Distribution in Beams with Irregular Cross-sections



$$\frac{M}{I} = \frac{\sigma}{y} = \frac{E}{R}$$

$$\frac{\partial M_x}{\partial R_A} = x, \frac{\partial M_x}{\partial M_A} = -1$$

M.O.I = 2I Limits of x: 0 to 1m

Hence  $\int_A^C \frac{M_x}{EI} \frac{\partial M_x}{\partial R_A} dx = \int_0^1 \frac{(-M_A + R_A x)x}{2EI} dx$

$$= \frac{1}{2EI} \left( \frac{-M_A(1)^2}{2} + \frac{R_A(1)^3}{3} \right)$$

$$= \frac{1}{2EI} \left( \frac{R_A}{3} - \frac{M_A}{2} \right)$$

And  $\int_A^C \frac{M_x}{EI} \frac{\partial M_x}{\partial R_A} dx = \int_0^1 \frac{(-M_A + R_A x)(-1)}{2EI} dx$

$$= \frac{1}{2EI} \left( M_A(1) - \frac{R_A(1)^2}{2} \right) = \frac{1}{2EI} \left( M_A - \frac{R_A}{2} \right)$$

For portion CB, Taking A as the origin we have

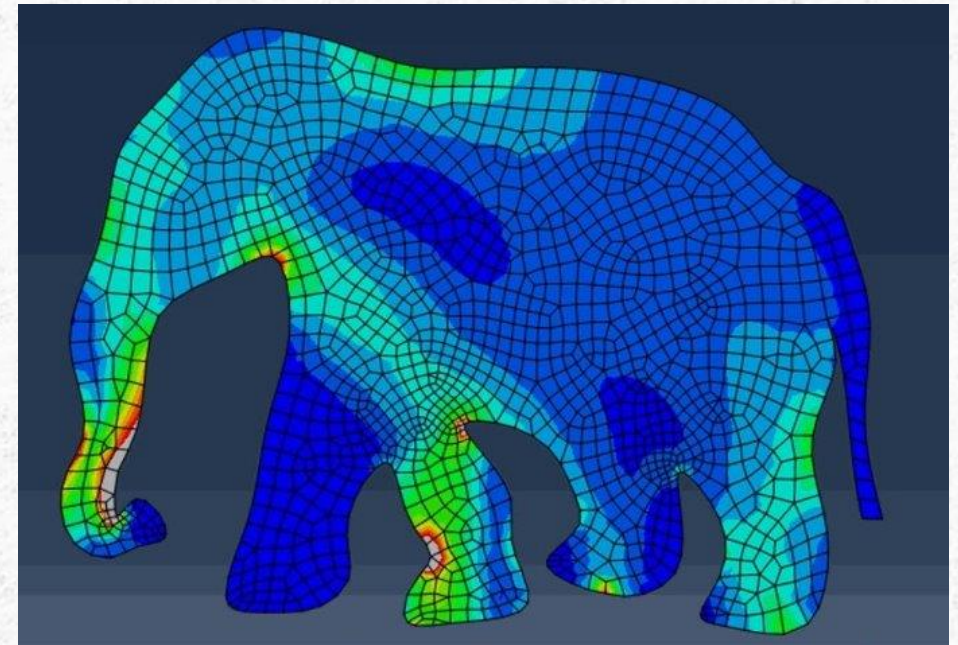
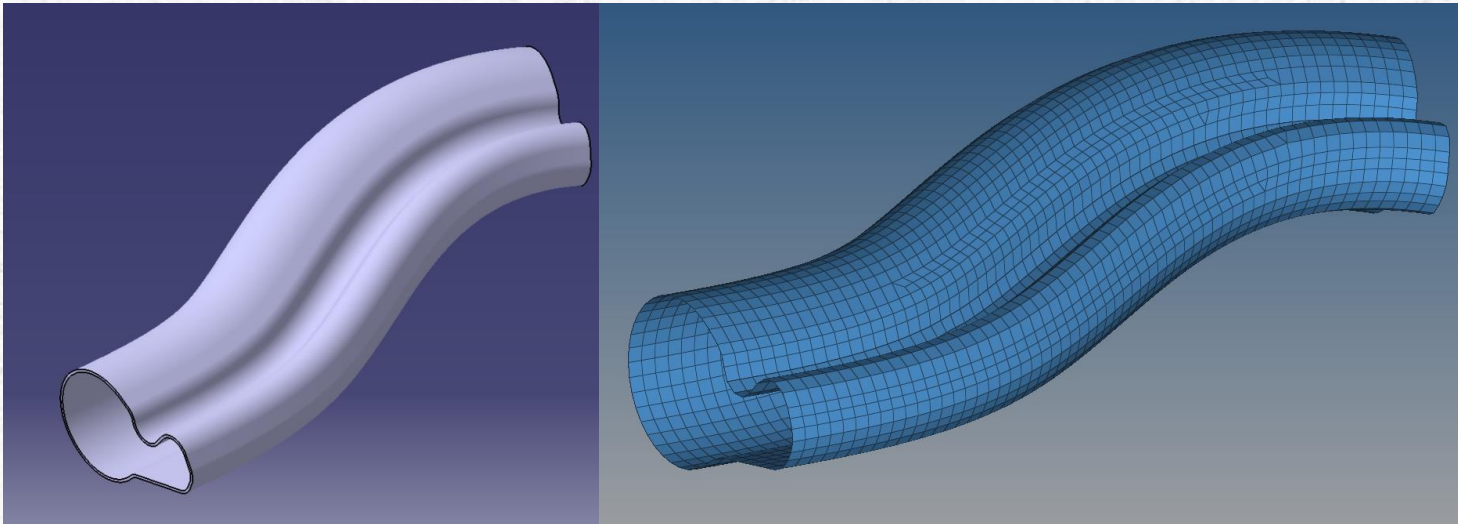
$$M_x = -M_A + R_A X - 9(X-1)$$

$$\frac{\partial M_x}{\partial R_A} = x, \frac{\partial M_x}{\partial M_A} = -1$$

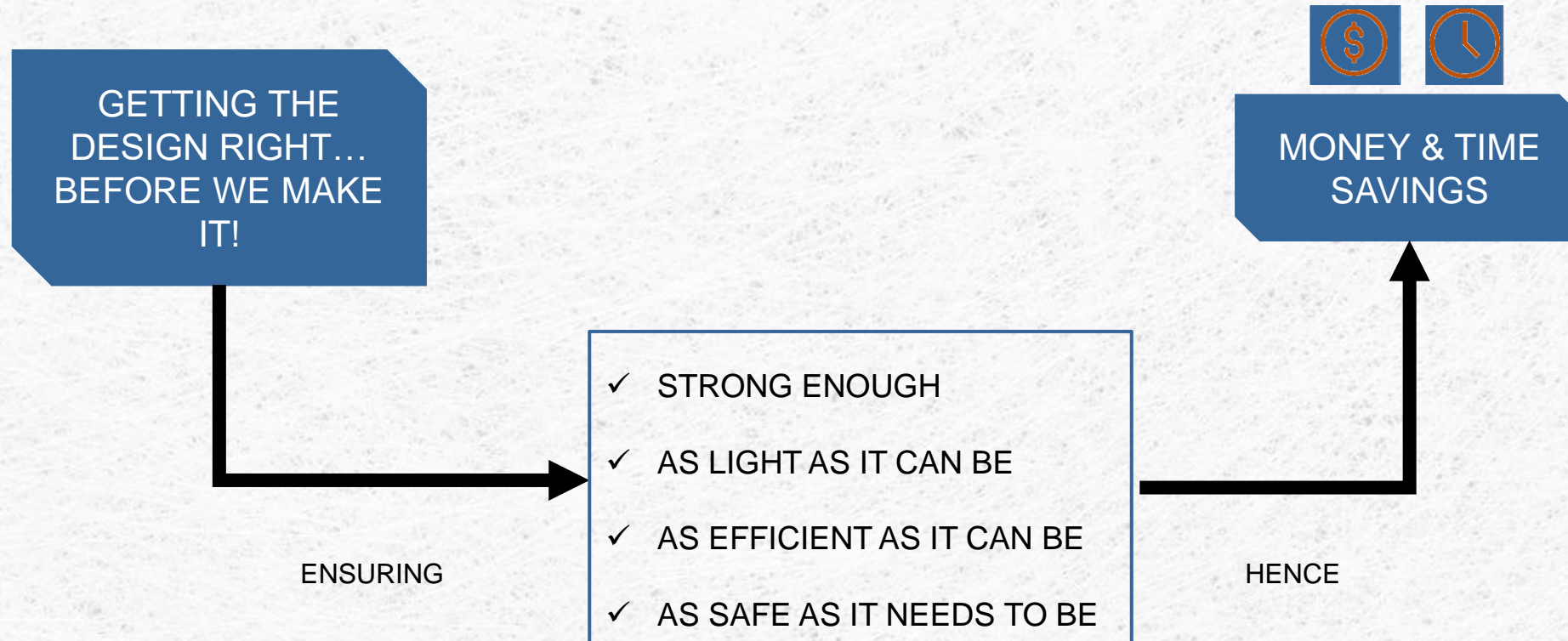
M.O.I = I

Limits of x : 1 to 3 m

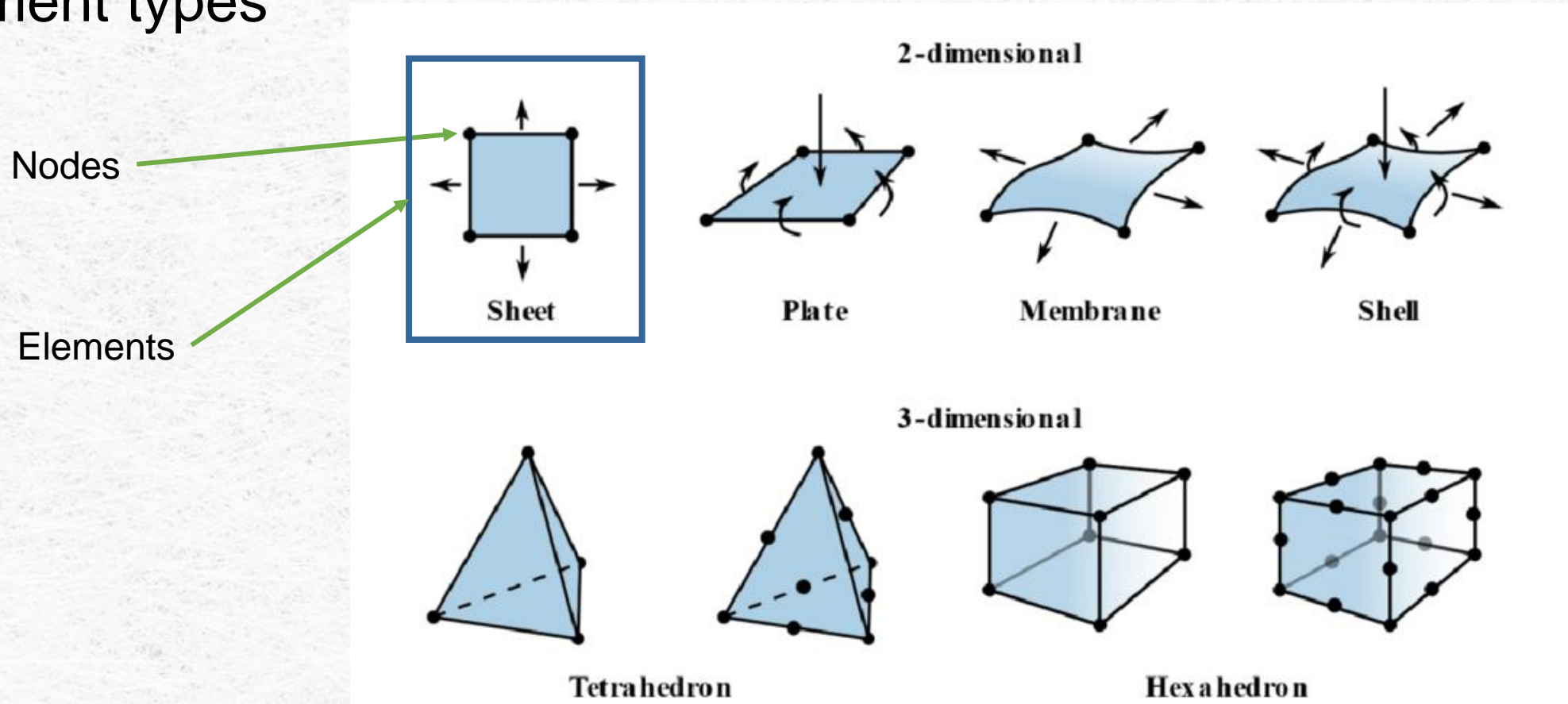
## FEA approach



## FEA approach

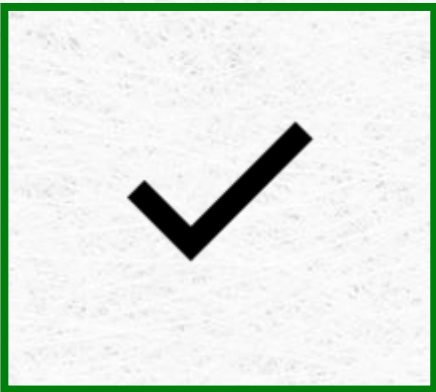


## Element types



## Deviations from ideal shape

Perfect/Ideal shape



Regular shape

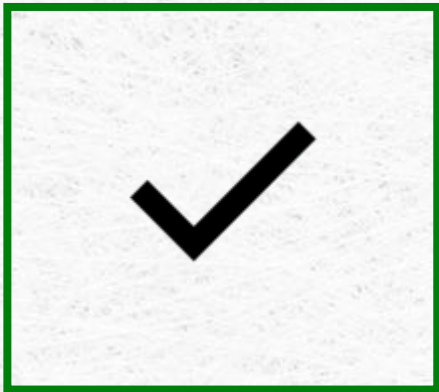


Bad shape



## Deviations from ideal shape

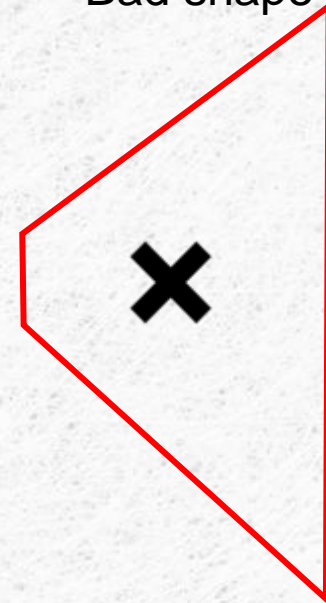
Perfect/Ideal shape



Regular shape

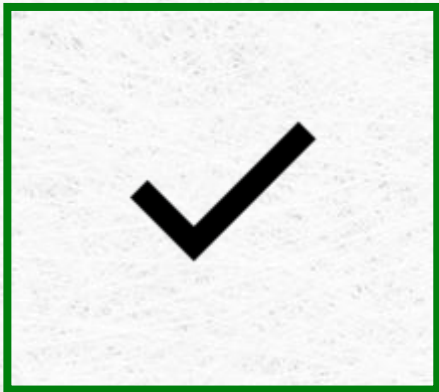


Bad shape

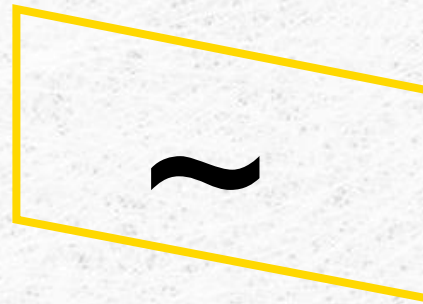


## Deviations from ideal shape

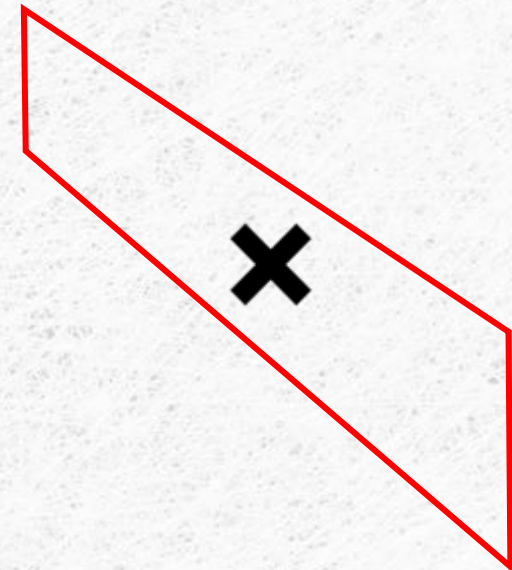
Perfect/Ideal shape



Regular shape

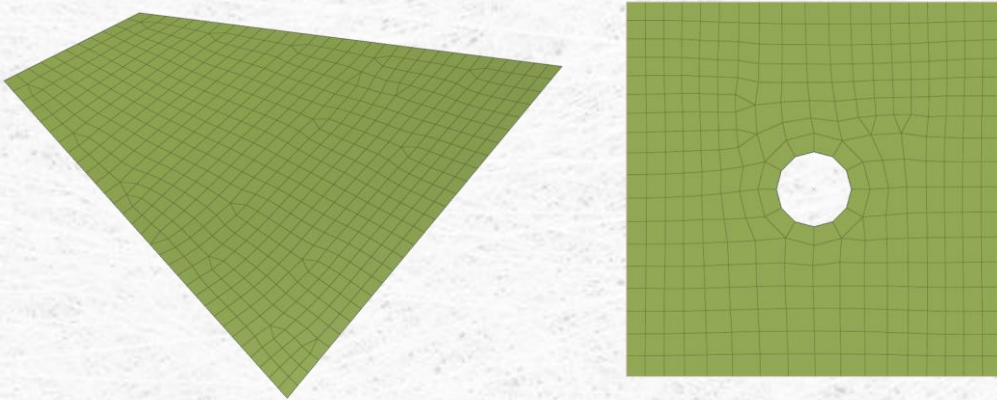


Bad shape

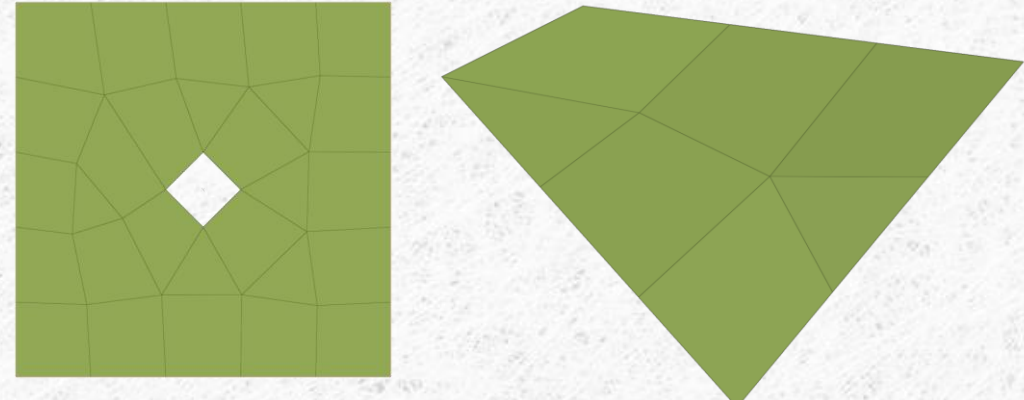


## Discretization level

Good geometry discretization/resolution



Bad geometry discretization/resolution



Mesh size should be defined according to the smallest feature you want to capture in the model

## Discretization level

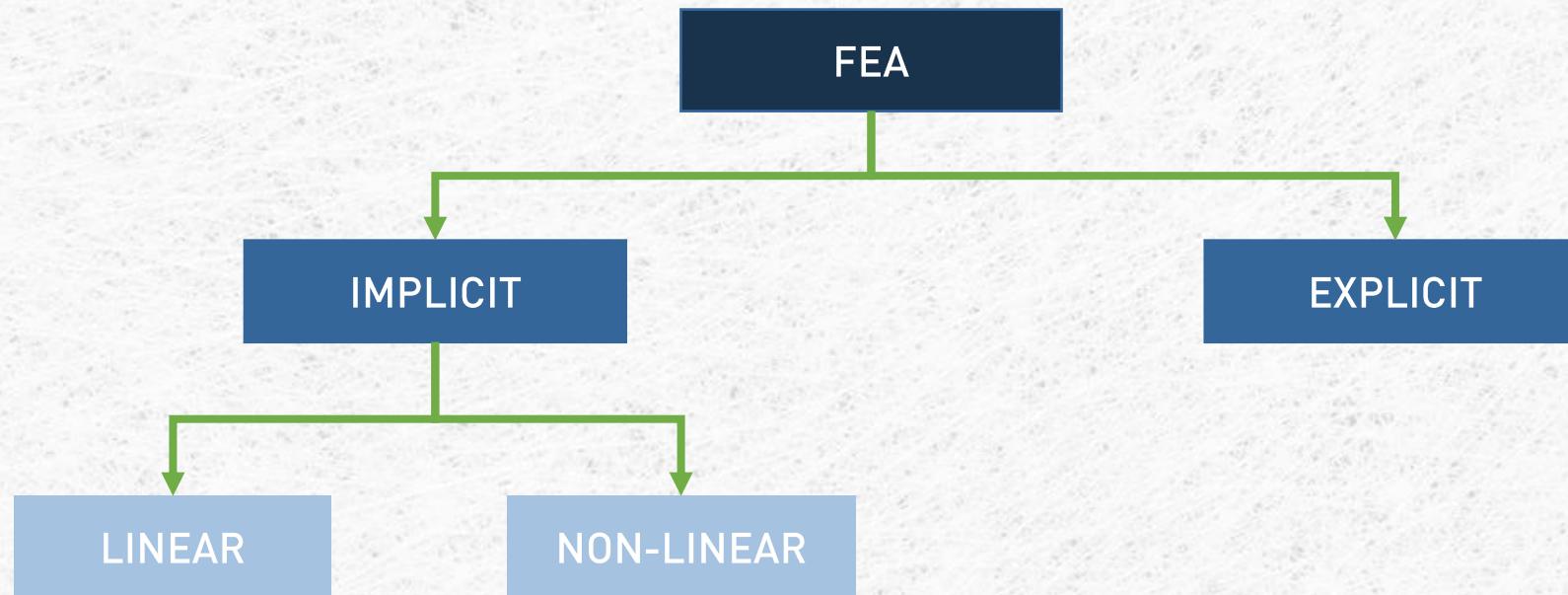
Good picture resolution



Bad picture resolution



## Types of analyses



## Types of analyses - Linear Implicit

Lineal static analysis is based on the following equation

$$F = K \cdot u$$

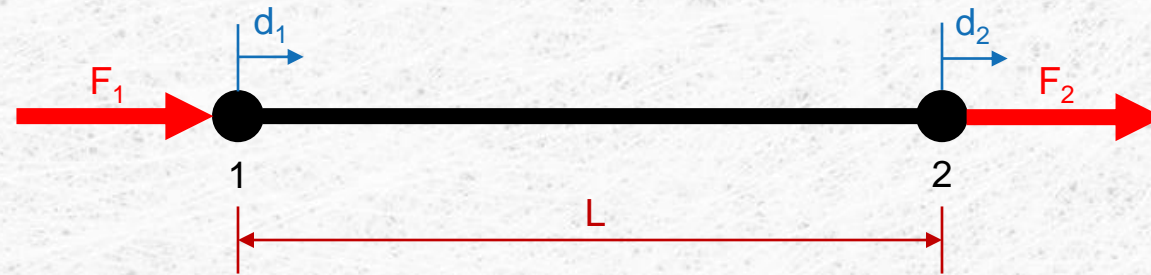
Where:

$F$  is the vector which contains external/reaction loads and moments

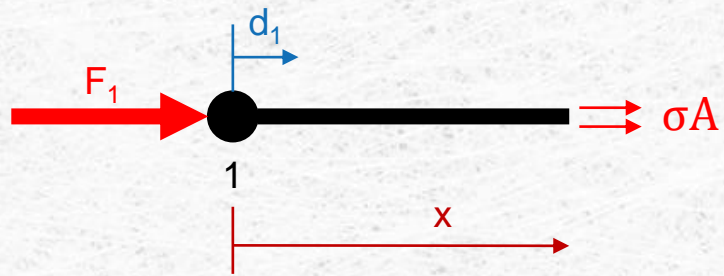
$K$  is the stiffness matrix

$u$  is the displacement and rotation vector

## Types of analyses - Linear Implicit



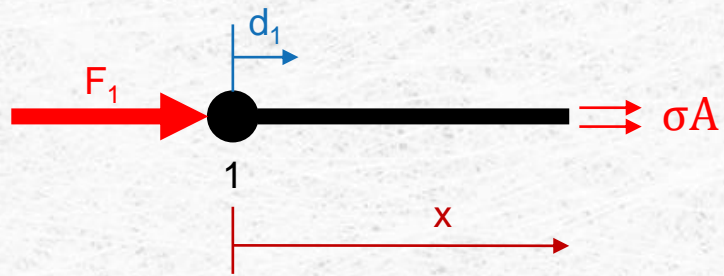
## Types of analyses - Linear Implicit



STRESS & STRAIN:

$$\left. \begin{aligned} \sigma &= E\varepsilon \\ \varepsilon &= \frac{du}{dx} \end{aligned} \right\} \sigma = E \frac{du}{dx}$$

## Types of analyses - Linear Implicit

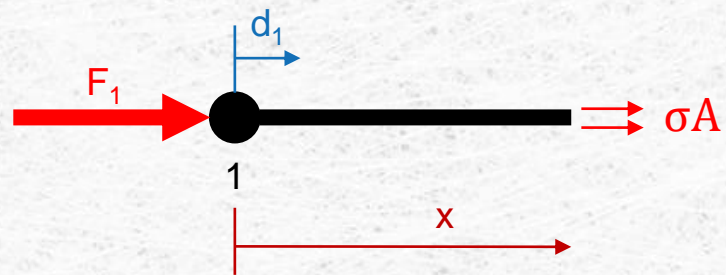


EQUILIBRIUM:

$$F_1 + \sigma A = 0 \longrightarrow F_1 + EA \frac{du}{dx} = 0$$

$$F_1 x + EAu + C = 0$$

## Types of analyses - Linear Implicit



BOUNDARY CONDITIONS:

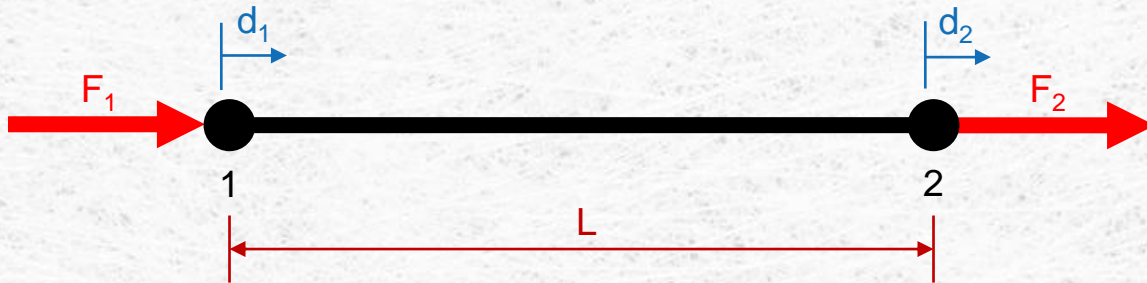
$$x = 0 \rightarrow u = d_1$$

$$EAd_1 + C = 0 \quad \longrightarrow \quad C = -EAd_1$$



$$F_1x + EAu - EAd_1 = 0$$

## Types of analyses - Linear Implicit



BOUNDARY CONDITIONS:

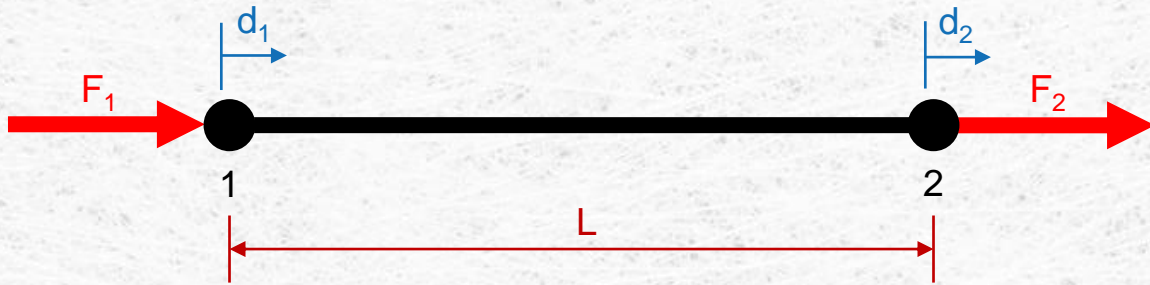
$$x = 0 \rightarrow u = d_1$$

$$EAd_1 + C = 0 \quad \longrightarrow \quad C = -EAd_1$$



$$F_1x + EAu - EAd_1 = 0$$

## Types of analyses - Linear Implicit



$$F_1 = \frac{EA}{L} (d_1 - d_2)$$

$$F_2 = \frac{EA}{L} (-d_1 + d_2)$$

$$\begin{pmatrix} F_1 \\ F_2 \end{pmatrix} = \frac{EA}{L} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{pmatrix} d_1 \\ d_2 \end{pmatrix}$$

K



$$F = K \cdot u$$

## Types of analyses - Non-linear Implicit

In the non-linear analysis the following equation does not hold true due to the following sources:

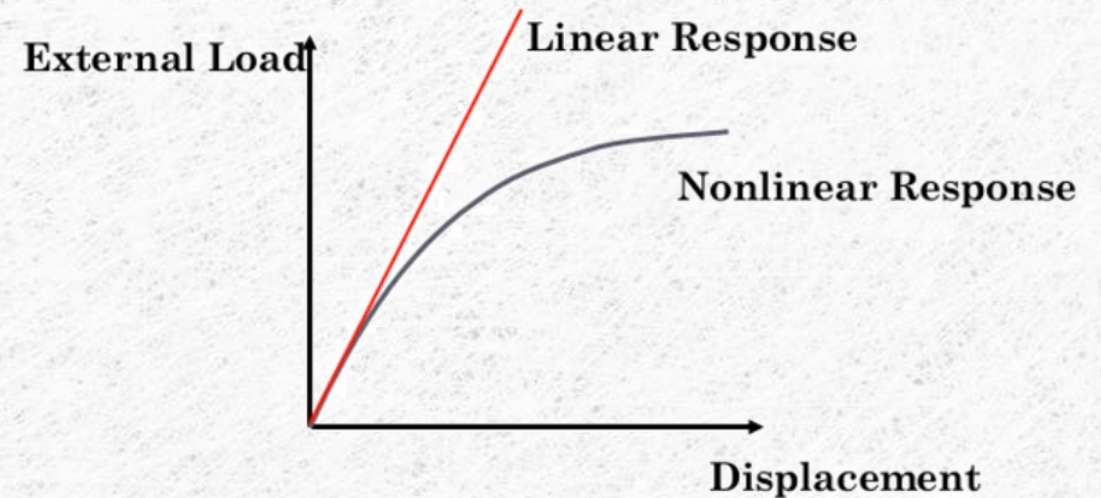
- Geometric non-linearity
- Material non-linearity
- Constraint and contact non-linearity
- Follower load

$$F \neq K \cdot u$$

## Types of analyses - Non-linear Implicit

### Geometric non-linearity

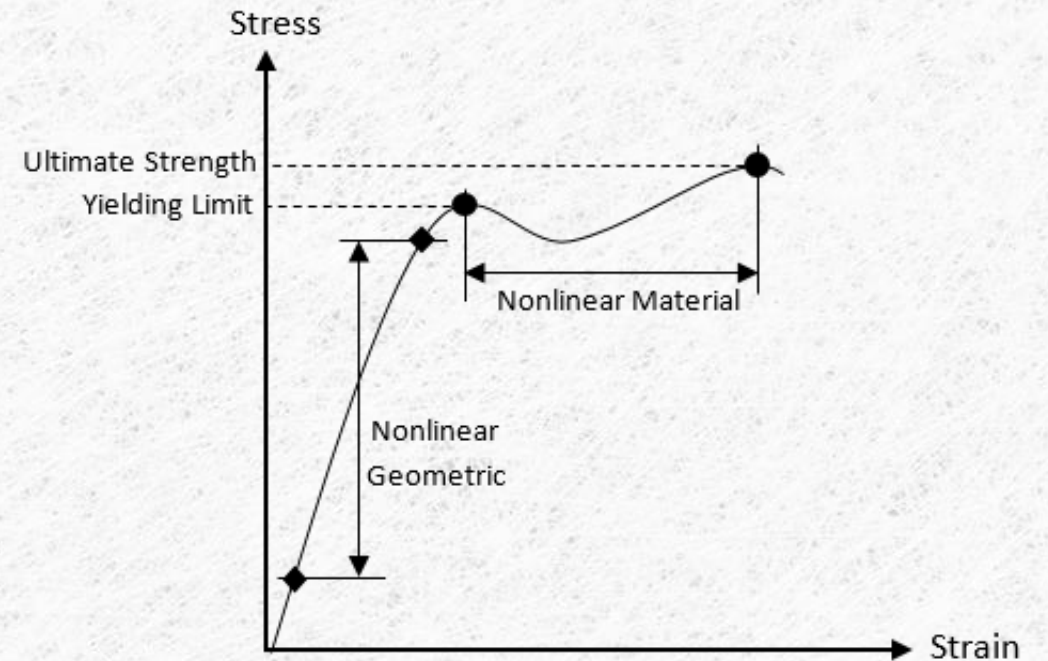
- In analyses involving geometric non-linearity, changes in geometry as the structure deforms are considered in formulating the constitutive and equilibrium equations.
- Large displacements can produce this type of non-linearity behavior.



## Types of analyses - Non-linear Implicit

### Material non-linearity

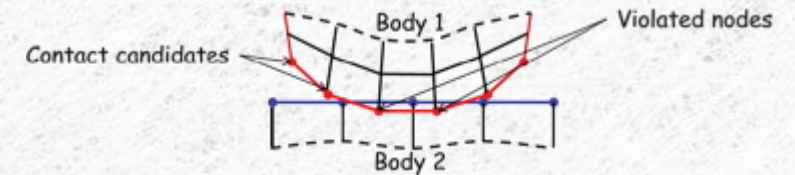
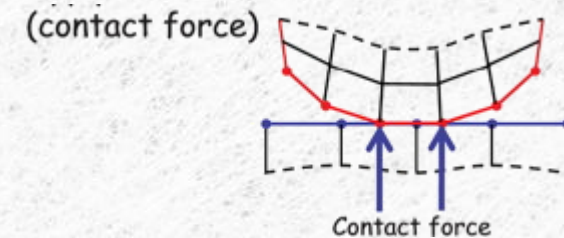
- Material nonlinearity involves the nonlinear behavior of a material based on current deformation, deformation history, rate of deformation, temperature, pressure, and so on.



## Types of analyses - Non-linear Implicit

### Constraint and contact non-linearity

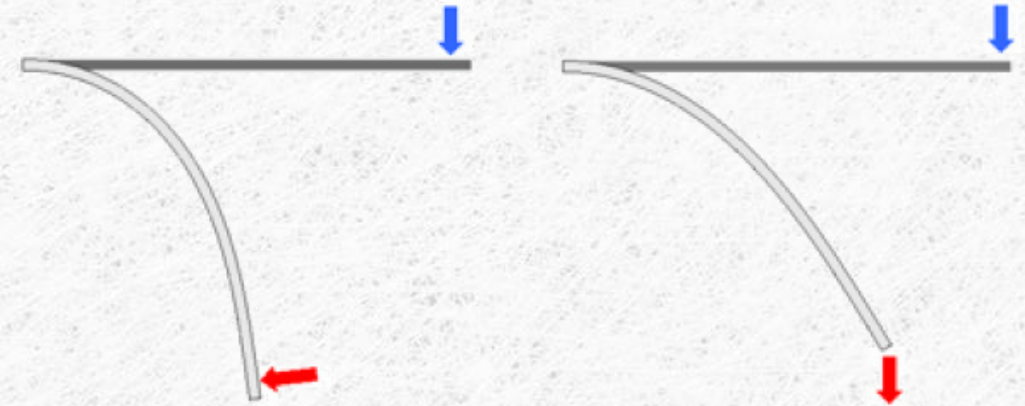
- Constraint nonlinearity in a system can occur if kinematic constraints are present in the model. The kinematic degrees-of-freedom of a model can be constrained by imposing restrictions on its movement.
- In the case of contact, the constraint condition is based on inequalities and such a constraint generally does not allow penetration between any two bodies in contact.



## Types of analyses - Non-linear Implicit

### Follower load non-linearity

- Applied loads can depend upon the deformation of the structure when large deformations are involved. Geometrically, the applied loads (Forces or Pressure) can deviate from their initial direction based on how the model deforms at the location of application of load.



## Types of analyses - Non-linear Implicit

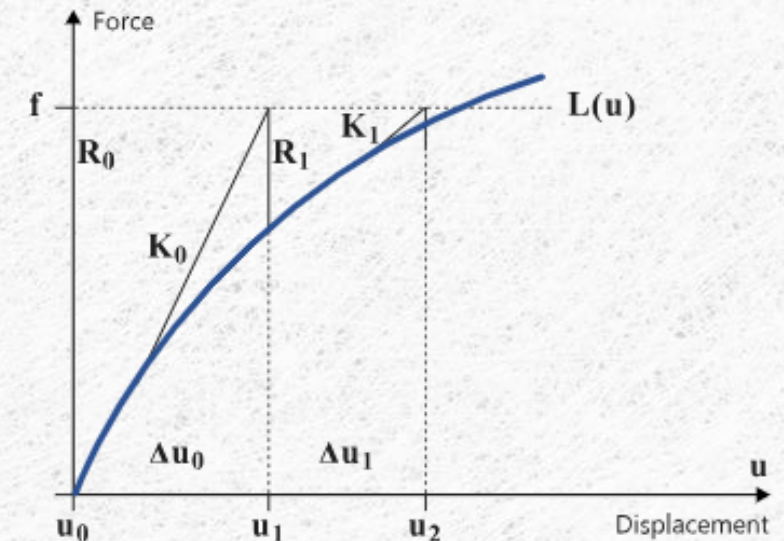
Nonlinear problems are generally history dependent. In order to achieve a certain level of accuracy, the solution must be obtained in a series of small increments.

$$L(u) = f \quad K_n \Delta u_n = R_n \quad u_{n+1} = u_n + \Delta u_n$$

$$K_n = \left( \frac{\partial L(u)}{\partial u} \right)_{u_n} \quad R_n = f - L(u_n)$$

Where:

- $u_n$  is the displacement vector
- $f$  is the global load vector
- $L(u)$  is the global non-linear response of the system
- $R_n$  is the non-linear residual



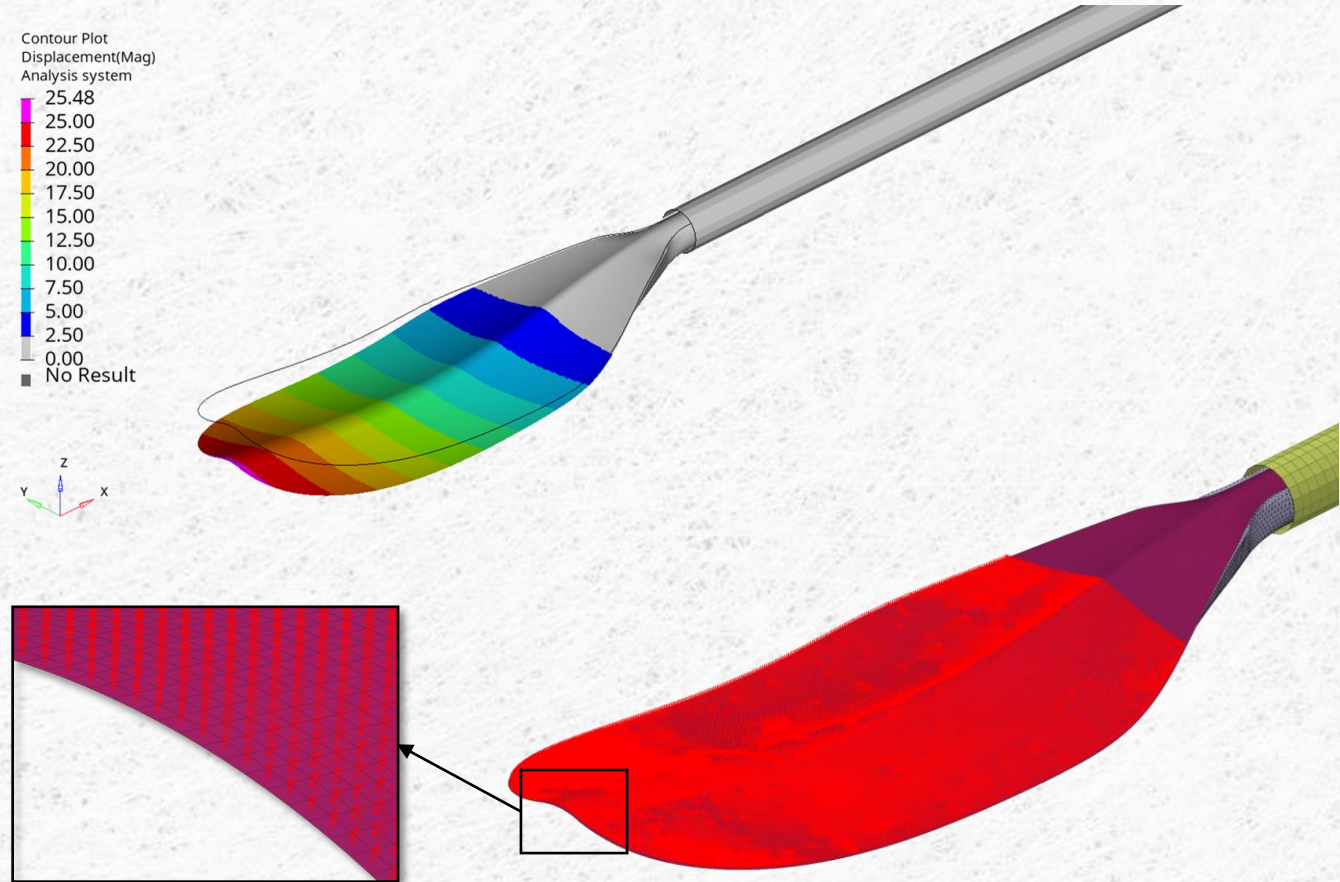
## Types of analyses - Non-linear Implicit - MC4 Specific Application

### ANALYSIS TYPE

- ▶ Non-linear Implicit static analyses
  - ▶ **Large displacements** due to **geometry** were considered
  - ▶ **Follower load** non-linearity must be considered
  - ▶ Cohesive **contact** iteration between paddle and paddle reinforcement

### DETAILS

- ▶ Load defined equally distributed in all main sub stack layer nodes
- ▶ Oar included to define a most precise boundary conditions



## Types of analyses - Explicit

Explicit FEA is based (roughly) on the following equation:

Where:

- $f_e$  are the external forces
- $f_d$  are the damping forces
- $f_c$  are the contact forces
- $f_h$  are the hourglass forces
- $f_i$  are the element internal forces
- $m$  is the lumped mass matrix
- $a$  is the acceleration vector, computed directly from equilibrium equation

$$\sum F = m \cdot a \Rightarrow f_e + f_d + f_c + f_h - f_i = m \cdot a$$

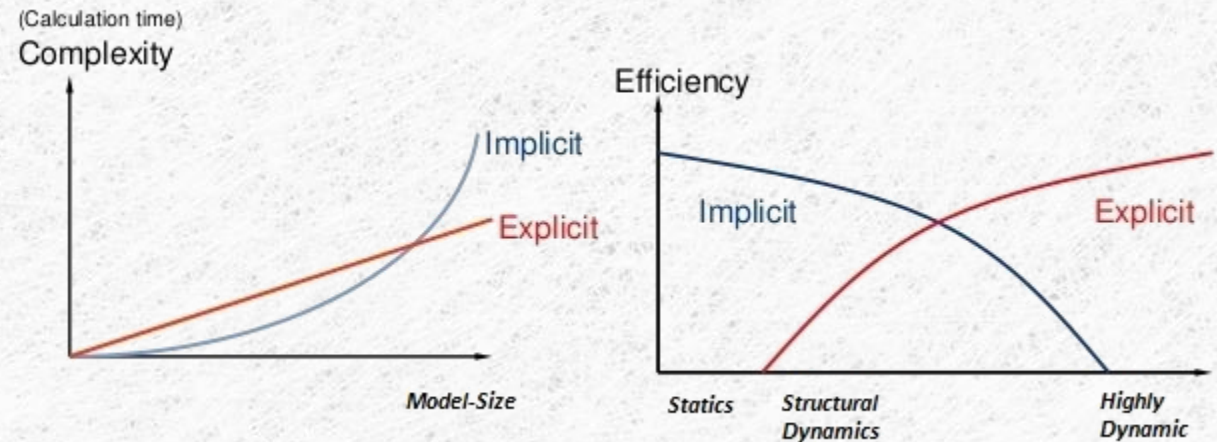
## Types of analyses - Explicit

### Implicit VS Explicit FEA technics

Explicit FEA is used to calculate the state of a given system at a different time from the current time.

When the physical problem has a strong time dependence, for instance a drop test, explicit scheme must be used

In contrast, when the physical problem can be considered as time independent, an implicit analysis should be used. One example could be when loads are slowly applied onto a structure.



## Types of analyses - Explicit

Explicit or implicit schemes must be chosen according to the complexity and efficiency of the numerical problem.

Unlike implicit analysis, explicit time integration scheme is conditionally stable.

Computational efficiency is strongly related with the time increment, which depends on two factors: element time step and/or nodal time step

Element time step

Nodal time step

## Types of analyses - Explicit

Element time step depends on the type of element used, but in short, the most important variables are:

Element size  $L$

Where:

- $\Delta t$  is the time increment
- $L$  is the element size
- $C$  is the speed of sound
- $E$  is the young's modulus
- $\rho$  is the material density

$$\Delta t = \frac{L}{c} \quad c = \sqrt{\frac{E}{\rho}}$$

Material young's modulus  $E$

Material density  $\rho$

## Types of analyses - Explicit

Nodal time step depends on the following variables:

Where:

- $\Delta t_n$  is the nodal time increment
- $m_n$  is the nodal mass
- $k_n$  is the equivalent nodal stiffness
- $k_e$  is the element stiffness
- $k_i$  is the interface stiffness (only in contact iteration regions!)

$$\Delta t_n = \sqrt{\frac{2m_n}{k_n}} \longrightarrow \text{Nodal time step}$$

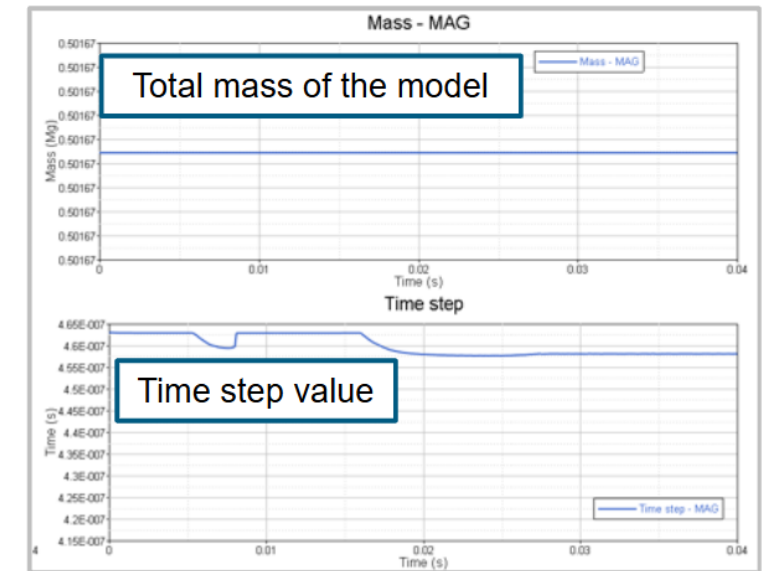
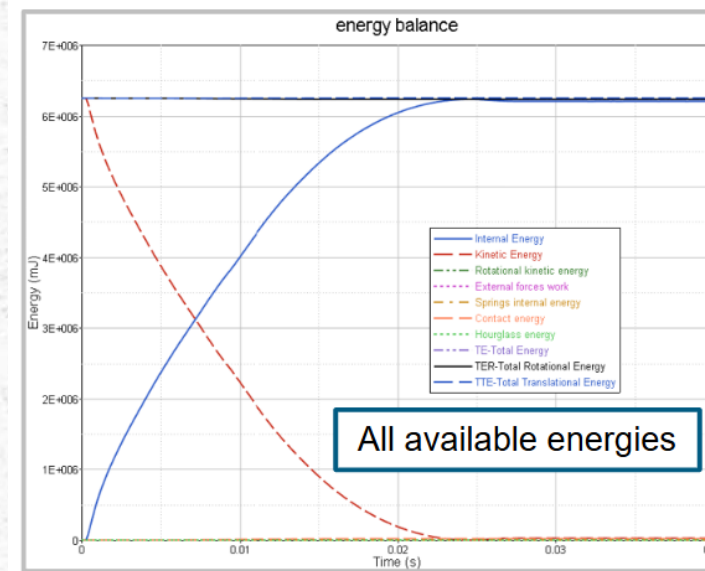
$$\Delta t_n = \sqrt{\frac{2m_n}{k_e + k_i}} \longrightarrow \text{Interface time step}$$

## Types of analyses - Explicit

### Computational checks

Due to the stable integration scheme, the following steps should be checked to get an accurate result:

- Energy balance
- Mass balance
- Momentum balance
- Time step evolution
- Visual inspection of deformed parts



## Types of analyses - Explicit

### Energy balance

Taking into account the external works, the total energy must remain constant or decrease slightly (maximum recommended of 5%).

The total hourglass energy must remain lower than 10% of the total energy.

The contact energy is not really physical. For each subset and for each part, the energy must remain lower than 15% of the total energy

$$\%Error = \frac{E_k + E_k^r + E_i}{E_{k1} + E_{k1}^r + E_{i1} + E_{wk} - E_{wk1}}$$

- $E_k$  is the translational kinetic energy
- $E_k^r$  is the rotational kinetic energy
- $E_i$  is the internal energy
- $E_{wk}$  is the external work
- $E_{k1}$  initial translational energy
- $E_{k1}^r$  initial rotational energy
- $E_{i1}$  initial internal energy
- $E_{wk1}$  initial external work

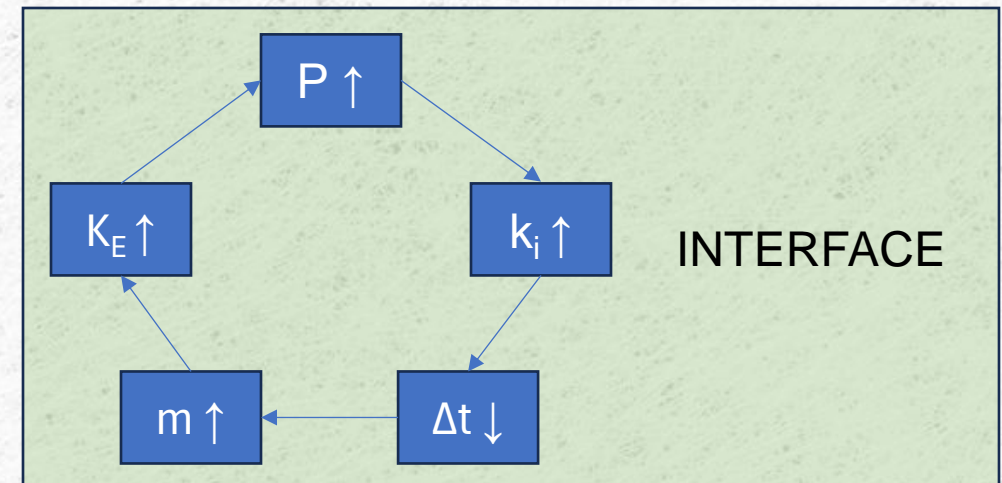
## Types of analyses - Explicit

### Mass balance

If the mass increases, its variation must remain smaller than 1% for each subset and for each part ( $\frac{dM}{M} < 1\%$ ). If the mass variation is between 1% to 3%, check if the nodes with the added mass are moving or not. If this is the case, the added mass results in an increase in kinetic energy. For more than 3% of variation, the results are probably bad.

### Usual issues:

- Imposed time step too high
- Material property poorly defined
- Large deformation
- Contact interface penetration P



## Types of analyses - Explicit

Momentum balance

The dynamic equilibrium of each node is satisfied by the Newton law at the end of each cycle.

Initial translational and rotational energies should be checked to ensure that the model has been build properly.

## Types of analyses - Explicit

### Time step evolution

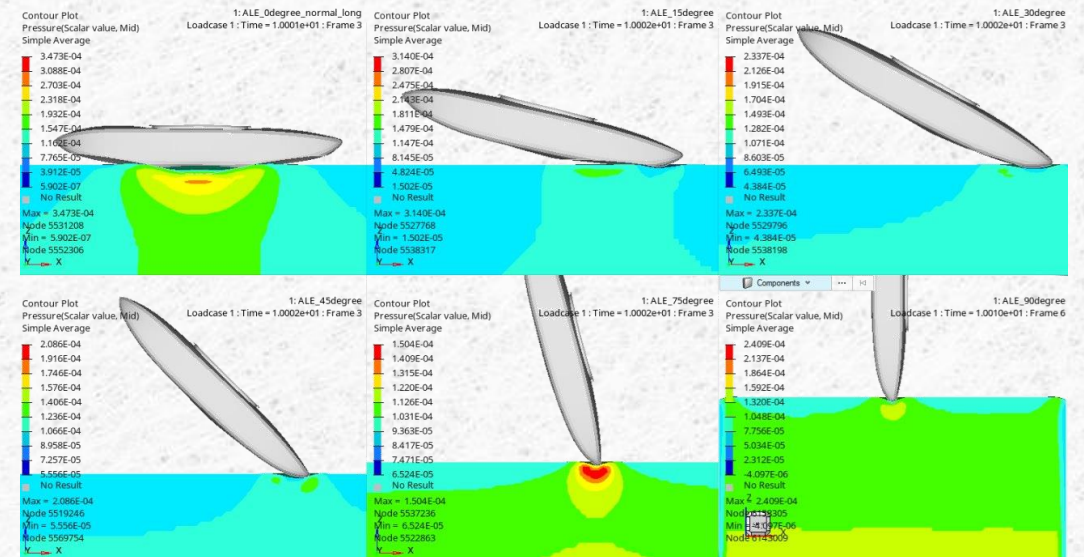
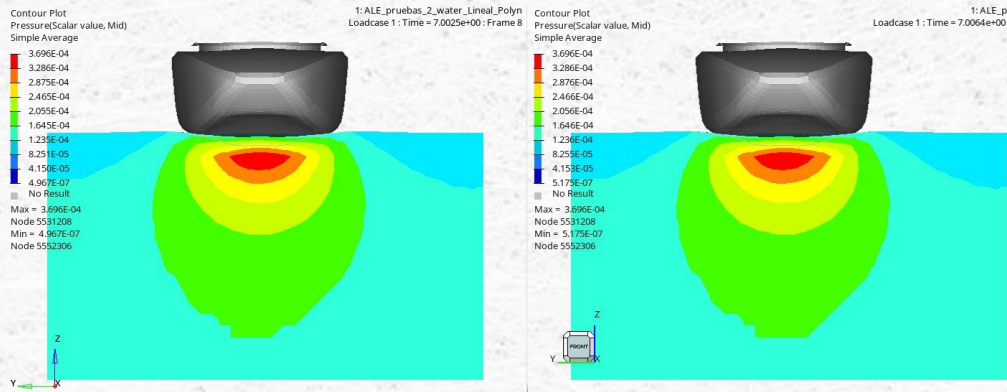
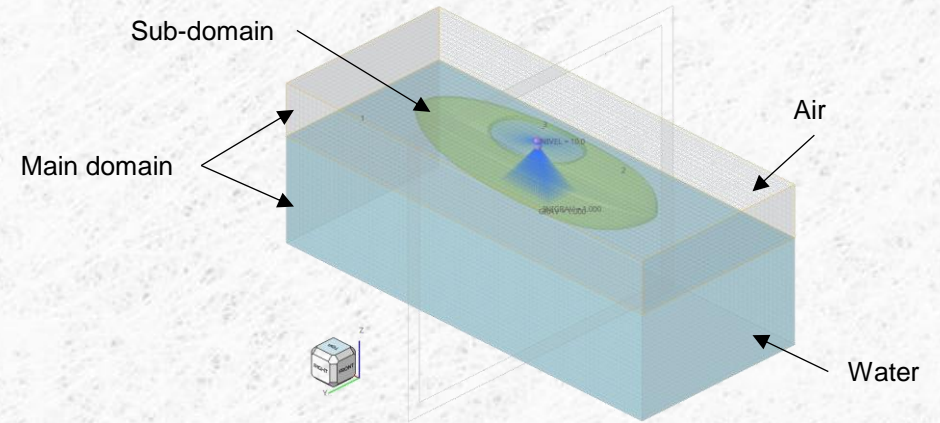
If the time step decreases and then it increases quickly, this is not a problem. If it varies greatly from one cycle to another, it may be due to the interface stiffness.

If the time step remains low, a problem has occurred. In this case, find the node (or element) controlling the time step and try to understand why the decrease occurred.

## Types of analyses - Explicit - MC4 Specific Application

An explicit approach has been used to reproduce the impact of a kayak falling from 5 meters height and different inclinations

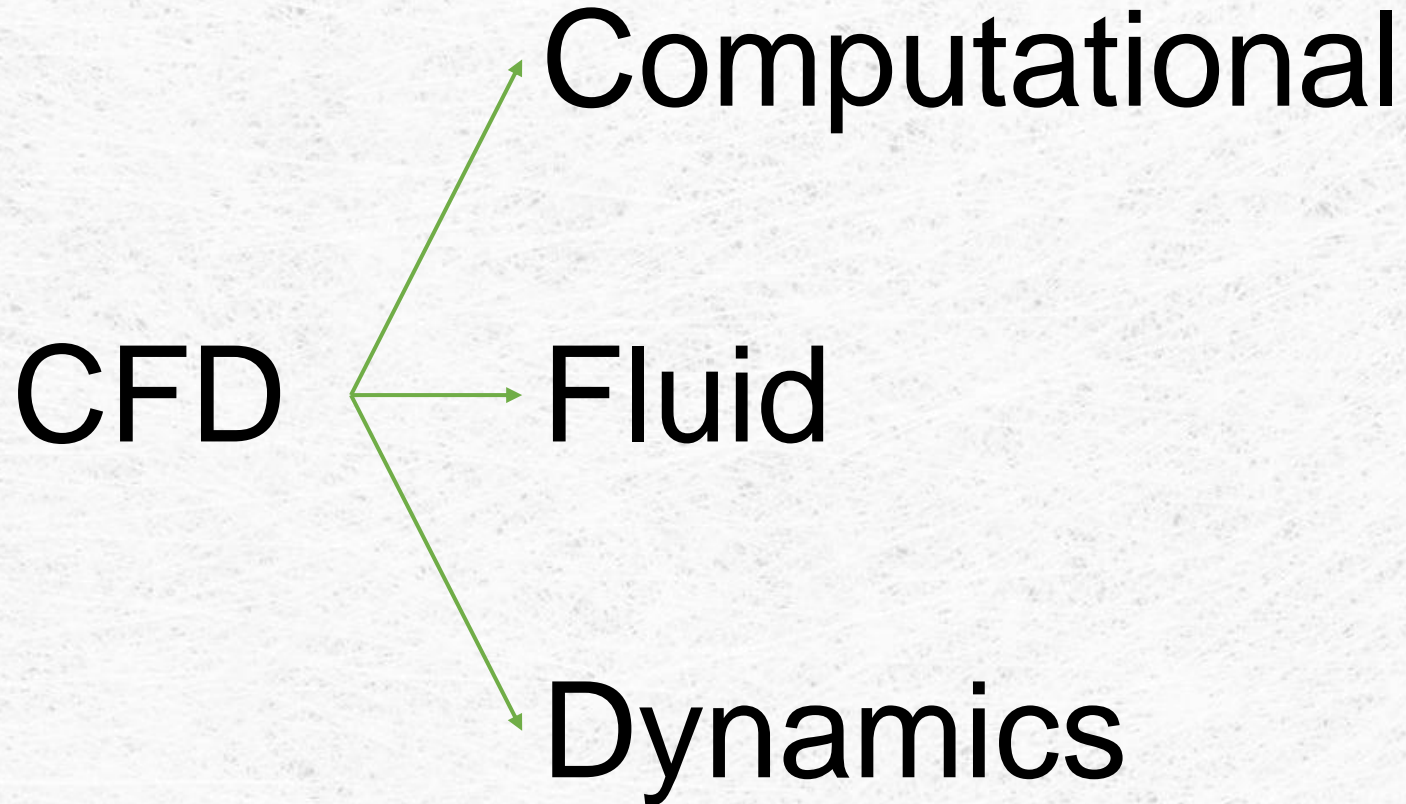
- ▶ The Multi-Domain method is used to optimize the computing performance
- ▶ ALE formulation as proved to be a good approach of the fluid-structure interaction. Material law 51 for multi-material
- ▶ Air is modeled through its equation of state properties, characterized by an ideal gas model



# Fundamentals of CFD



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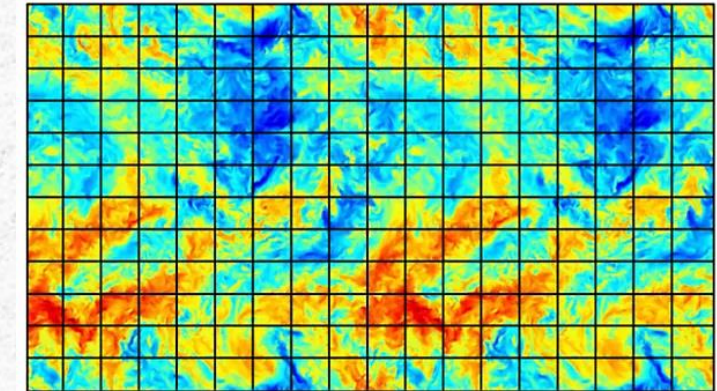
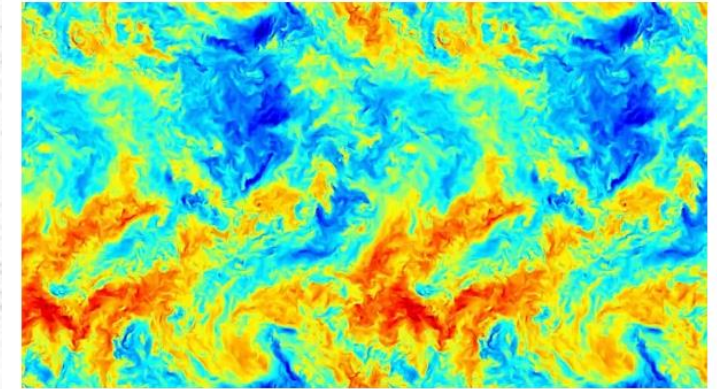
Computational fluid dynamics (CFD) is the science of using computers to predict liquid and gas flows based on the governing equations of conservation of mass, momentum, and energy.

Widely used to solve pressure and velocity fields and thermal physical problems.

## Introduction

The main features of the CFD analysis are:

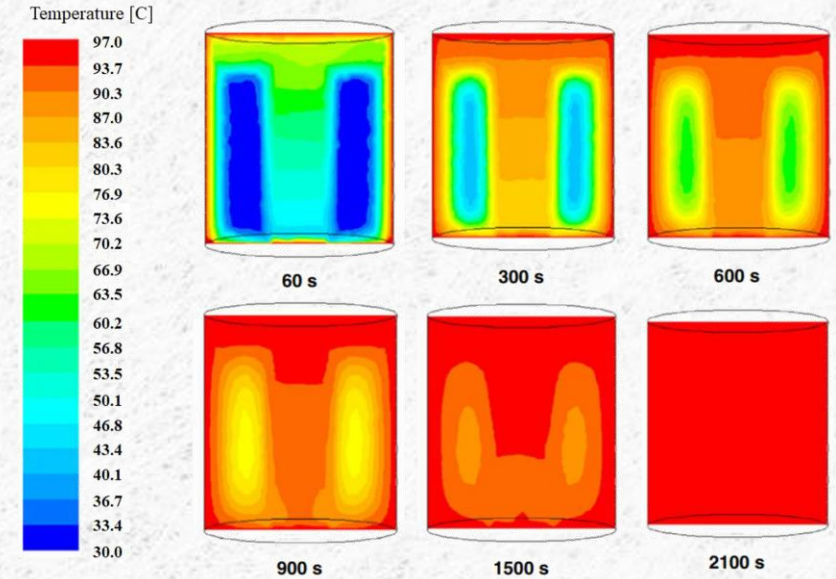
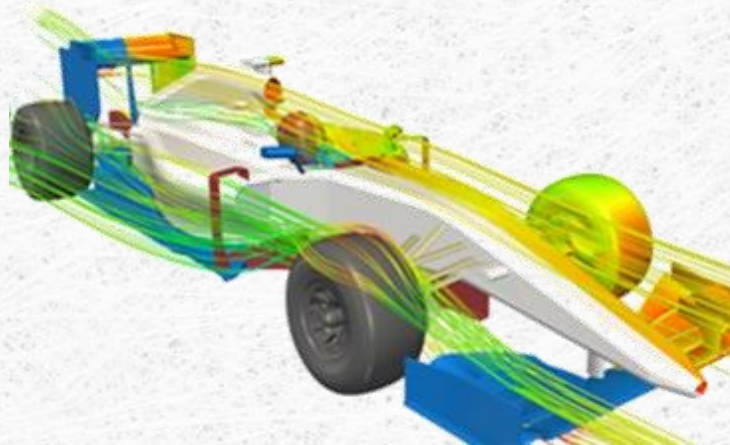
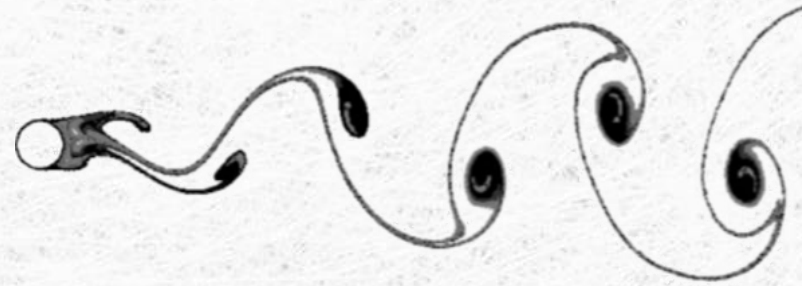
- Domain decomposition into cells (as FEA)
- Posing of the conservation equations in each cell (control volume)
- The system of partial derivative equations is discretized into a system of algebraic equations, then, is solved by iteration
- FVM (Finite Volume Method) is usually chosen to solve CFD problems as they involve conservation laws. It is widely used because of its Fundamentals conservation property.



## Introduction

Many different applications:

- Physics research
- External/internal aerodynamics
- External/internal hydrodynamics
- Thermal analysis



## Meshing

Mesh type and quality is one of the most important aspects, since it determines:

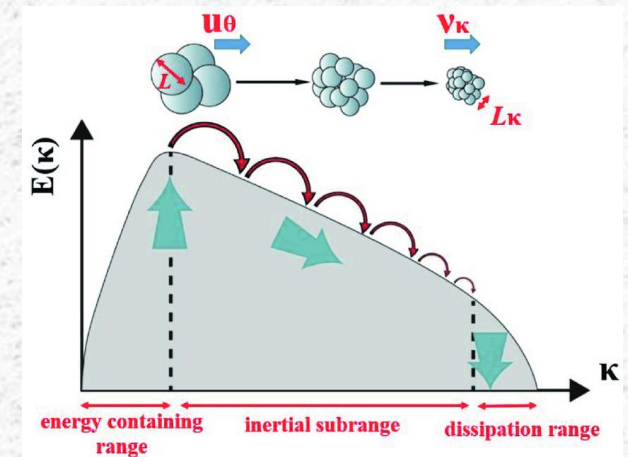
- Computational cost (number of cells). Usually much more expensive than FEA
- Accuracy (mesh quality)
- Convergence rate

Mesh types:

- Structural/regular/mapped mesh. Regular connectivity can be defined between elements, so, elements would be uniquely identified using as many index as there are dimensions of the meshed entry
- Non-structural/irregular mesh

## Models and fluid properties

- Reynolds Averaged Navier-Stokes (RANS)
  - Reynolds averaging, mean flow is solved.
  - Fluid fluctuations are included as additional terms in the mean flow equations
  - All scales of the turbulence are modeled by using the turbulent viscosity (Boussinesq hypothesis)
- Large Eddy Simulation (LES)
  - Large flow scales are solved, while small scales are modeled.
  - More expensive than RANS and accurate.
- Direct Numerical Simulation (DNS)
  - All scales of turbulence are resolved
  - Only feasible for small/simple domains. Typically used in research application to improve RANS/LES models



Kolmogorov length scale	$\eta = \left(\frac{\nu^3}{\epsilon}\right)^{1/4}$
Kolmogorov time scale	$\tau_\eta = \left(\frac{\nu}{\epsilon}\right)^{1/2}$
Kolmogorov velocity scale	$u_\eta = (\nu\epsilon)^{1/4}$

## Boundaries

- Mass flow inlet
  - Converts to entry velocity in incompressible fluids
  - Mass flow, the direction of the speed, the temperature and the turbulent variables are imposed.
  - Pressure is extrapolated from the interior.
- Pressure (stagnation) inlet
  - Stagnation pressure is imposed, also, the velocity direction, stagnation temperature and turbulent variables
  - Static pressure and temperature from the interior is extrapolated
- Pressure outlet
  - Only pressure is imposed
  - The rest of the variables are extrapolated from the interior

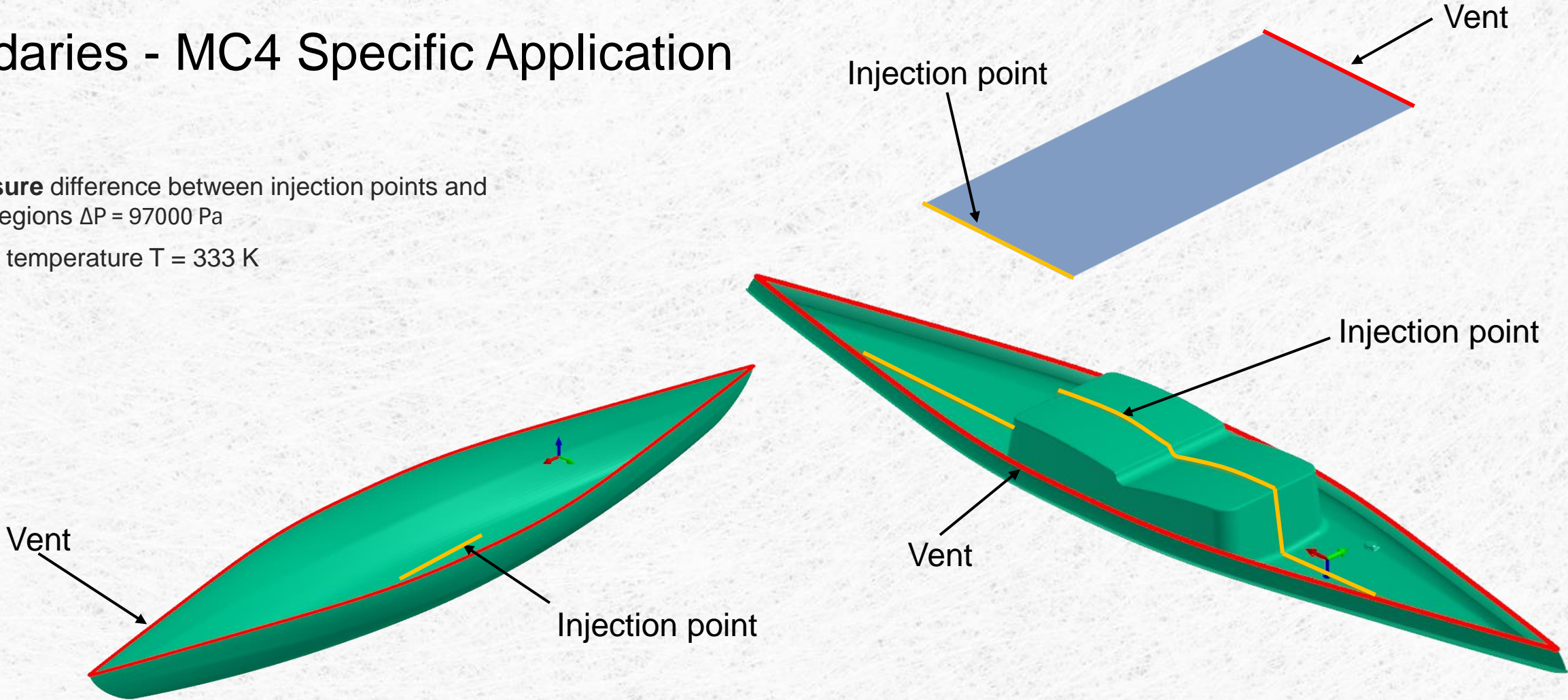
## Boundaries

- Pressure far field/free-stream (Riemann)
  - The imposed information is used to calculate the invariants of Riemann
  - Entropy and tangential velocity are imposed (input) or extrapolated from the interior (output)
  - It is a non-reflecting boundary condition (NRBC), typically in acoustics
- Wall
  - If the wall it is not porous, the normal speed is zero.
  - If the flow is viscous, the tangential velocity is zero (non-slip condition)
  - Pressure is extrapolated from the interior
  - The temperature is set on the wall or calculated from the interior temperature and heat flux established in the wall
- Symmetry

## Boundaries - MC4 Specific Application

### DETAILS

- ▶ **Pressure** difference between injection points and vent regions  $\Delta P = 97000 \text{ Pa}$
- ▶ Resin temperature  $T = 333 \text{ K}$



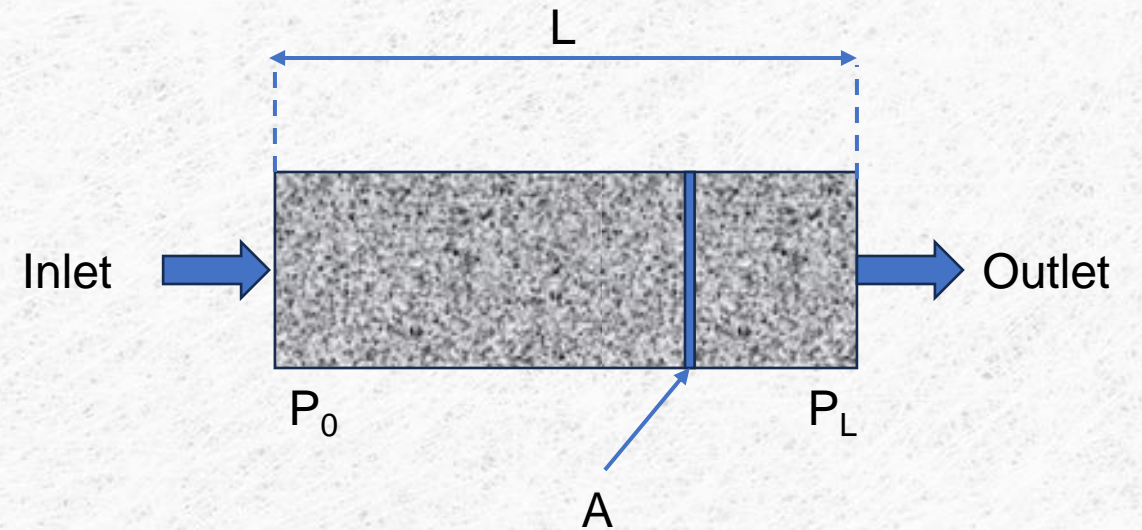
## Physical modelling – Flow in porous medium

Darcy's law 1D

Where:

- $Q$  is the flow rate
- $A$  is the cross section
- $K$  is the permeability
- $\mu$  is the viscosity
- $\Delta p$  is the pressure difference
- $L$  is the length

$$v = \frac{Q}{A} = \frac{K}{\mu} \cdot \frac{\Delta p}{L}$$

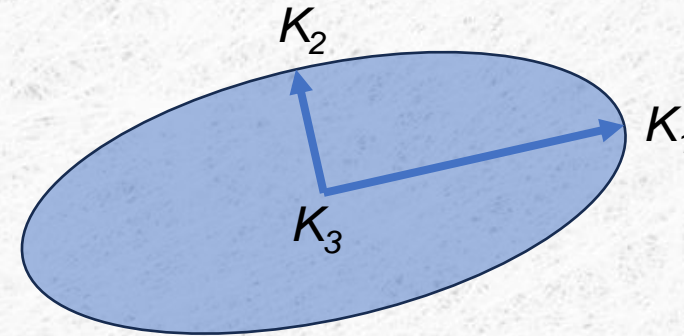


## Physical modelling – Flow in porous medium

### Darcy's law 3D

Where:

- $Q$  is the flow rate
- $A$  is the cross section
- $K$  is the permeability
- $\mu$  is the viscosity
- $\Delta p$  is the pressure difference
- $L$  is the length



$$\begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} = -\frac{1}{\mu} \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix} \cdot \begin{bmatrix} \partial p / \partial x \\ \partial p / \partial y \\ \partial p / \partial z \end{bmatrix} \longrightarrow [K] = \begin{bmatrix} K_1 & 0 & 0 \\ 0 & K_2 & 0 \\ 0 & 0 & K_3 \end{bmatrix}$$

## Physical modelling – Flow in porous medium

Darcy's law 3D

Fluid viscosity  $\mu(T)$  is a function of temperature  $T$

Permeability  $K$  is the key parameter to measure

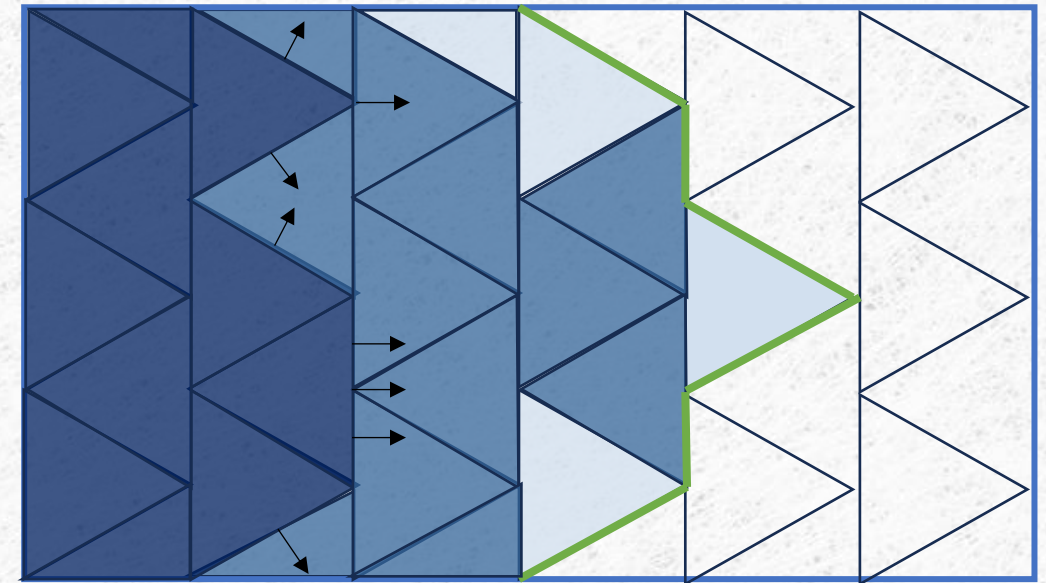
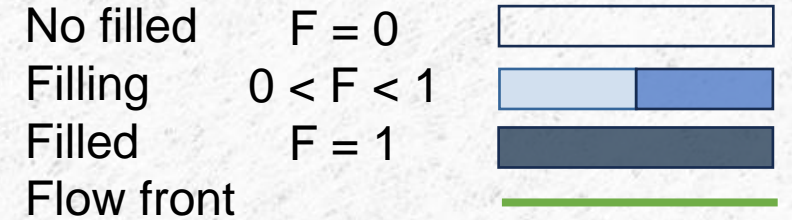
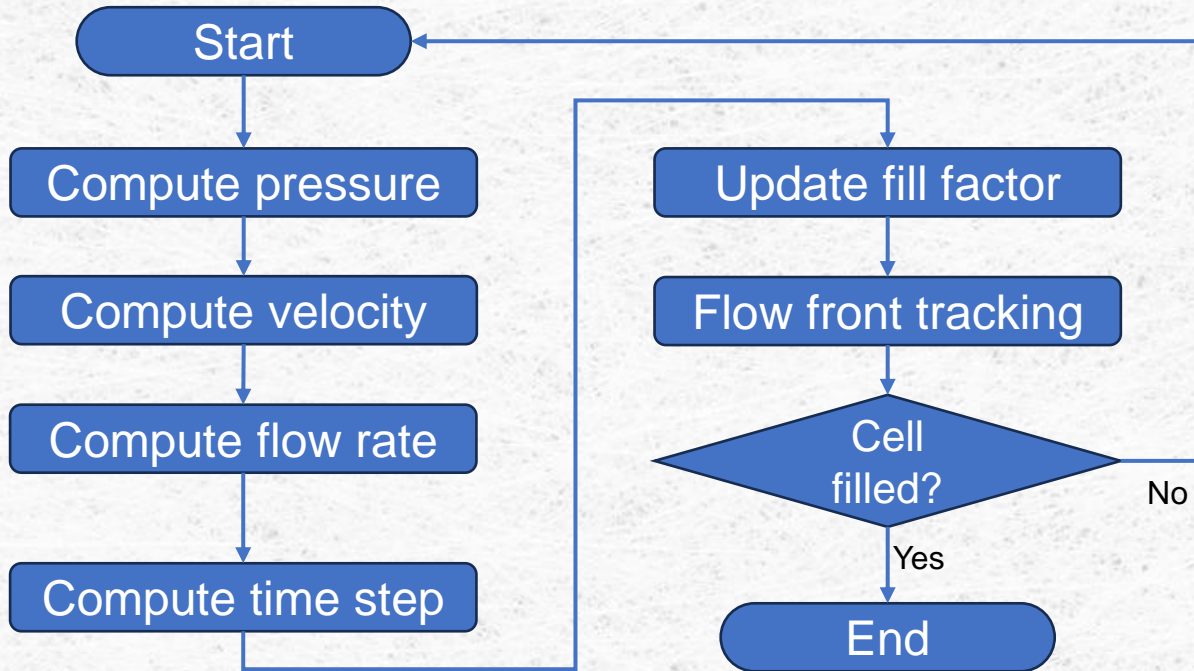
Fluid mass conservation equation solved every time step

$$v = \frac{[K]}{\mu} \cdot \nabla P$$

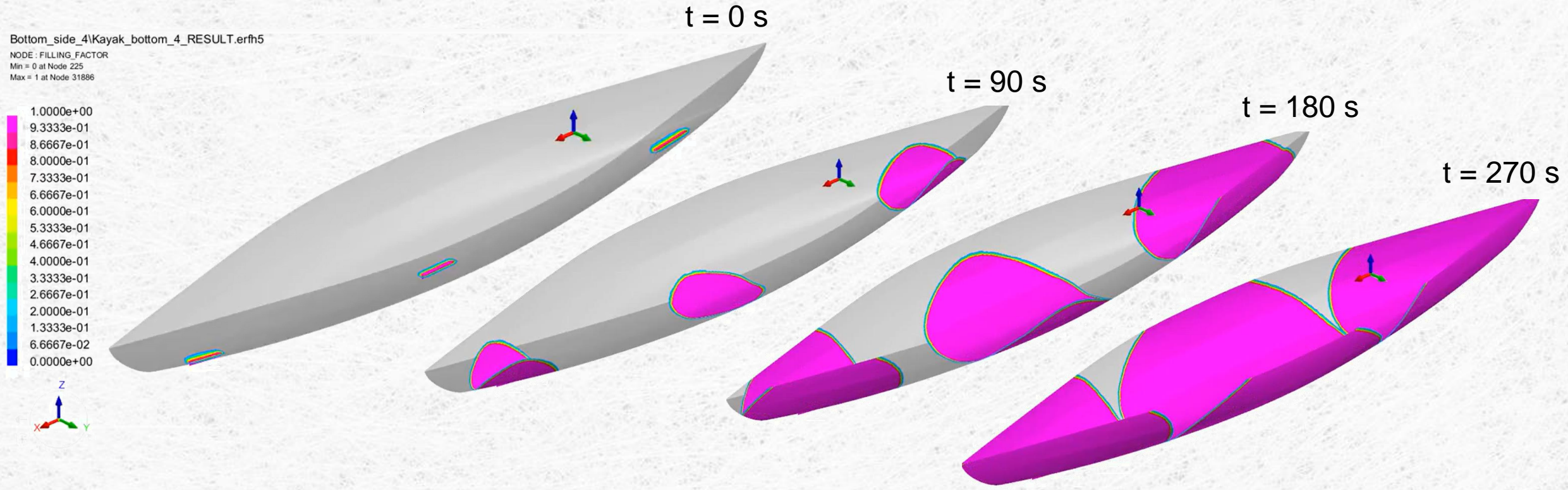
## Physical modelling – Flow in porous medium

### Darcy's law 3D

- Time step value changes at every step
- Time step is computed so that one row of elements is filled for each step



## Physical modelling – Flow in porous medium - MC4 Specific Application



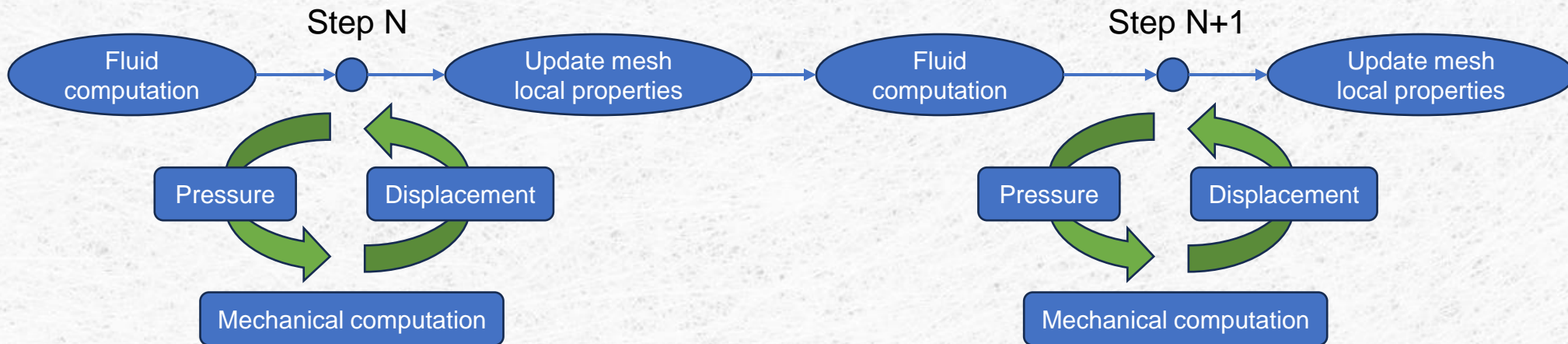
## Physical modelling – Flow in porous medium

### Mechanical coupling

Fluid mechanic coupled simulation

Permeability varies during filling

In case of mechanical coupling, mechanical equilibrium computation is done at time steps so that time between N and N+1 is equal to coupling period



## Physical modelling – Flow in porous medium

### Thermal equation

Where:

- $C_p$  is the specific heat of the porous medium
- $\rho$  is the density of the porous medium
- $C_{pr}$  is the specific heat of the fluid
- $\rho_r$  is the density of the fluid
- $\vec{v}$  is the fluid velocity
- $T$  is the temperature
- $\bar{k}$  is the thermal conductivity tensor
- $S$  is the source term

$$\begin{array}{cccc}
 \text{Dispersion} & \text{Transport} & \text{Diffusion} & \text{Source} \\
 \rho C_P \frac{\partial T}{\partial t} + \rho_r C_{pr} \vec{v} \cdot \nabla T = \nabla \cdot (\bar{k} \cdot \nabla T) + S
 \end{array}$$



# Structural simulations



Funded by  
the European Union

## Common sub-steps

The common steps for almost every FEA projects are:

Geometry clean-up

Meshing

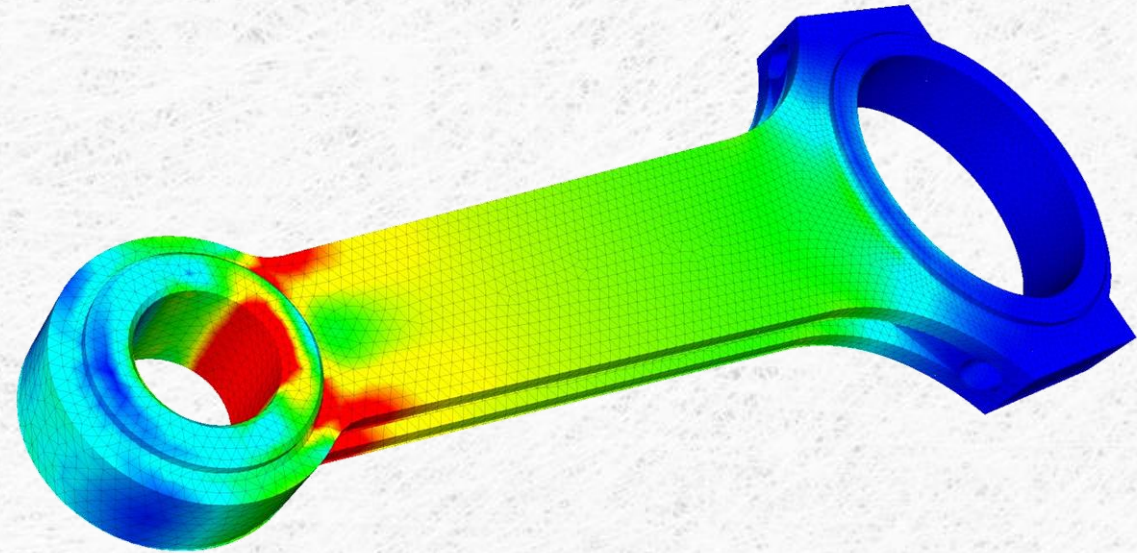
Pre-process

Model set-up

Analysis

Report results

Post-process



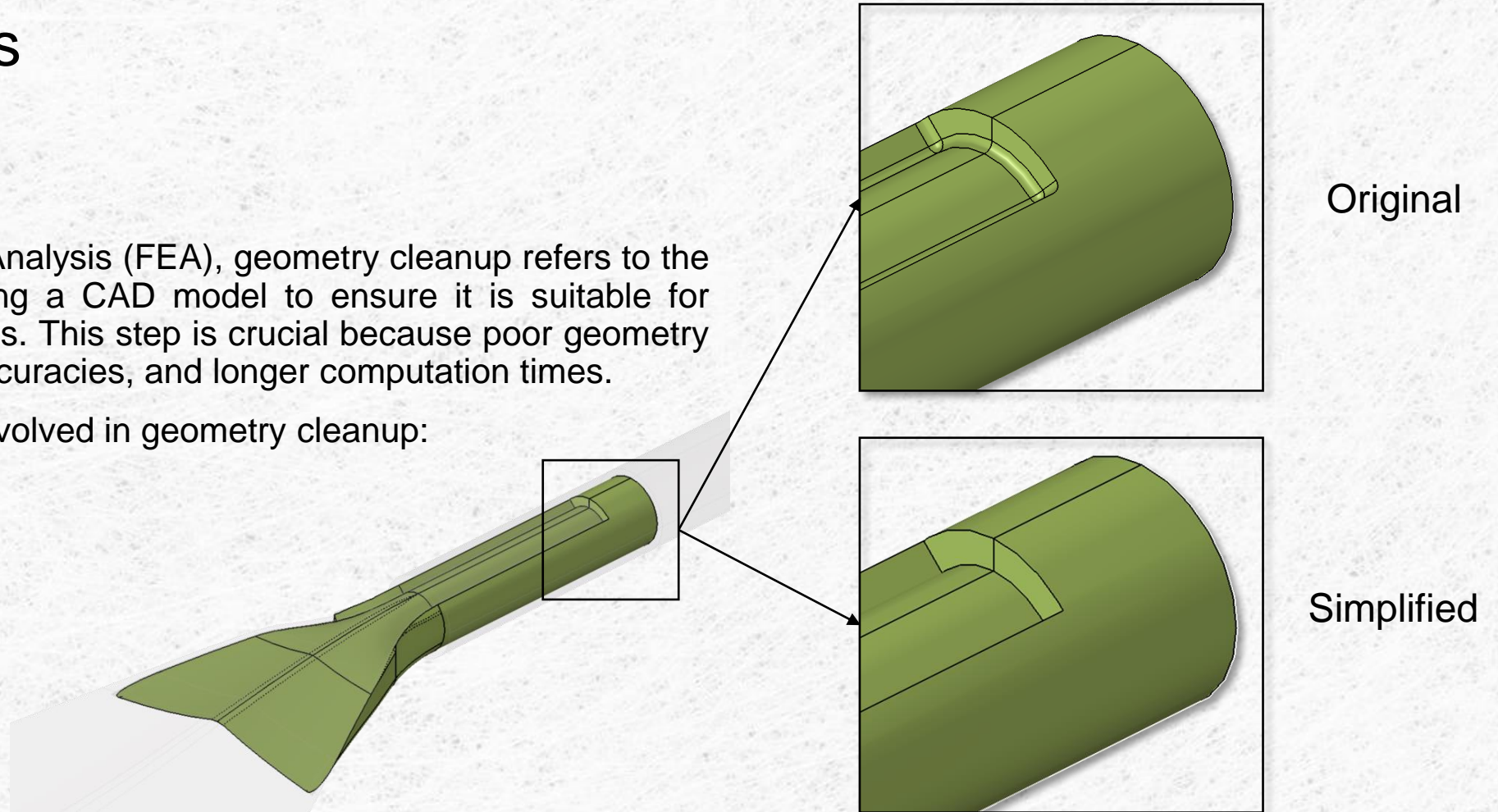
## Common sub-steps

### Geometry clean-up:

In the context of Finite Element Analysis (FEA), geometry cleanup refers to the process of preparing and refining a CAD model to ensure it is suitable for meshing and subsequent analysis. This step is crucial because poor geometry can lead to meshing issues, inaccuracies, and longer computation times.

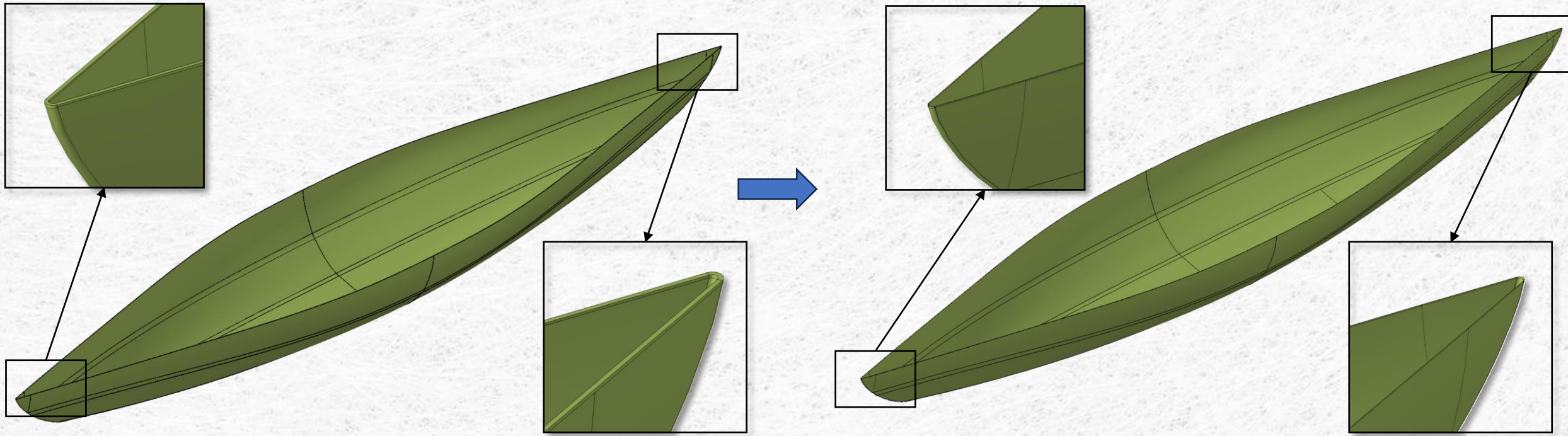
Here are some common tasks involved in geometry cleanup:

- Removing small features
- Repairing gaps and overlaps
- Simplify complex geometries
- Ensuring proper connectivity
- Defeaturing



## Common sub-steps

### Geometry clean-up - MC4 Specific Application



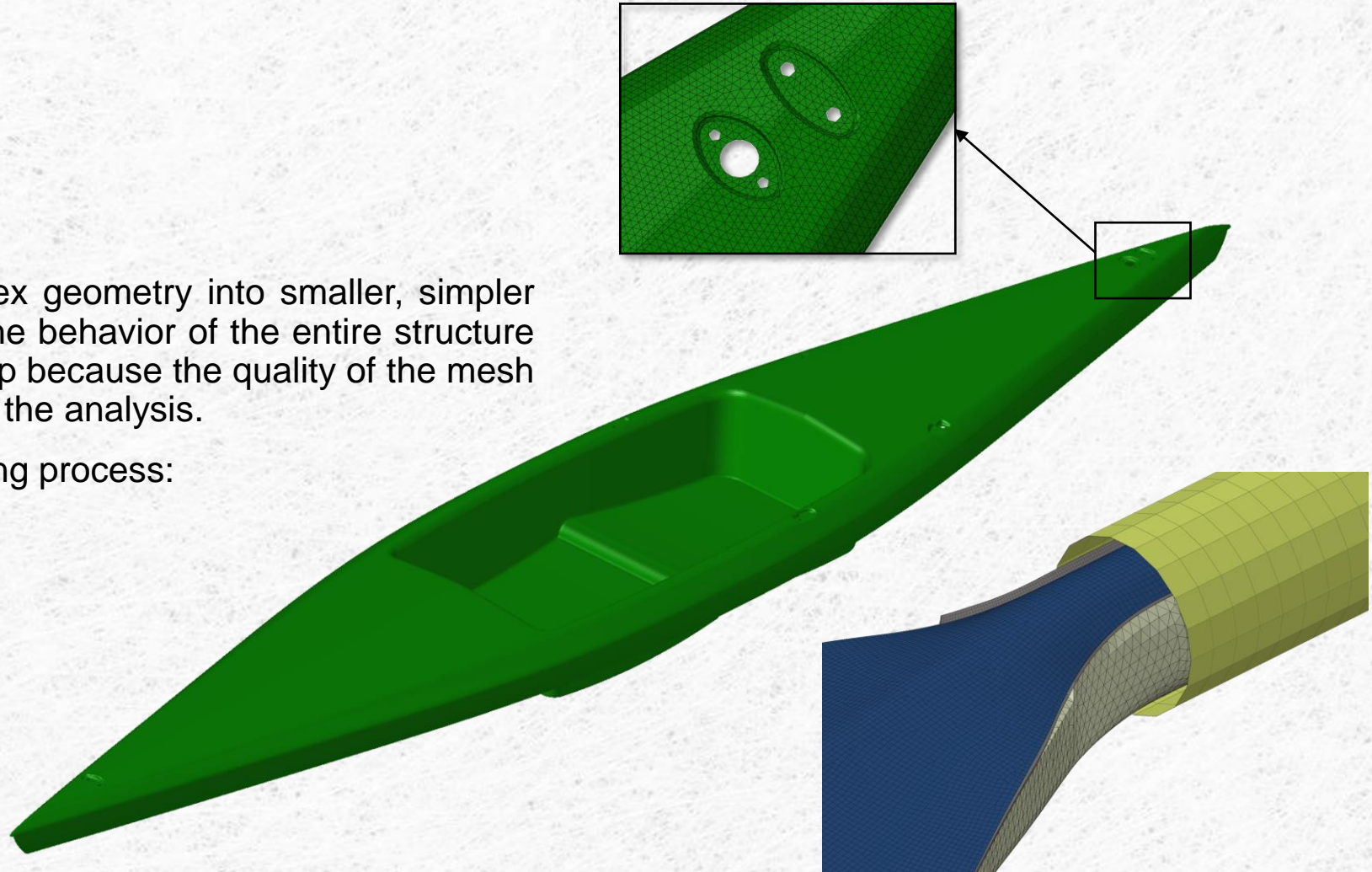
## Common sub-steps

### Meshing:

Meshing is the process of dividing a complex geometry into smaller, simpler elements that can be used to approximate the behavior of the entire structure under various conditions. This is a crucial step because the quality of the mesh directly affects the accuracy and efficiency of the analysis.

Here are the key steps involved in the meshing process:

- Element Type Selection
- Mesh Generation
- Mesh Refinement
- Quality Check



## Common sub-steps

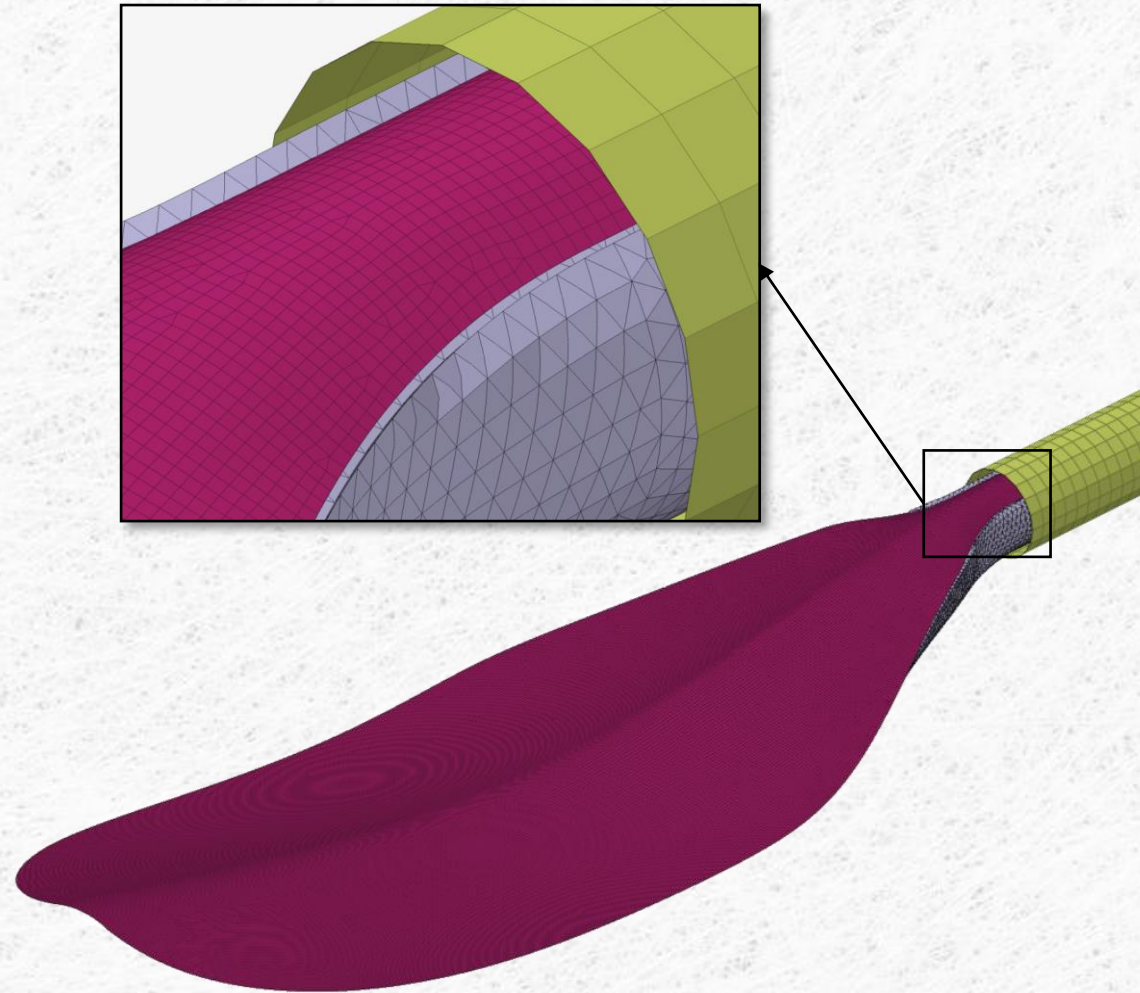
### Meshing - MC4 Specific Application

#### ELEMENT TYPES

- ▶ Paddle and oar: 2D shell elements (quadratic and triangular shape)
- ▶ Paddle reinforcement: 3D tetrahedral elements

#### ELEMENT SIZE

- ▶ Paddle: 1 mm
- ▶ Reinforcement: 2 mm
- ▶ Oar: 5 mm



## Common sub-steps

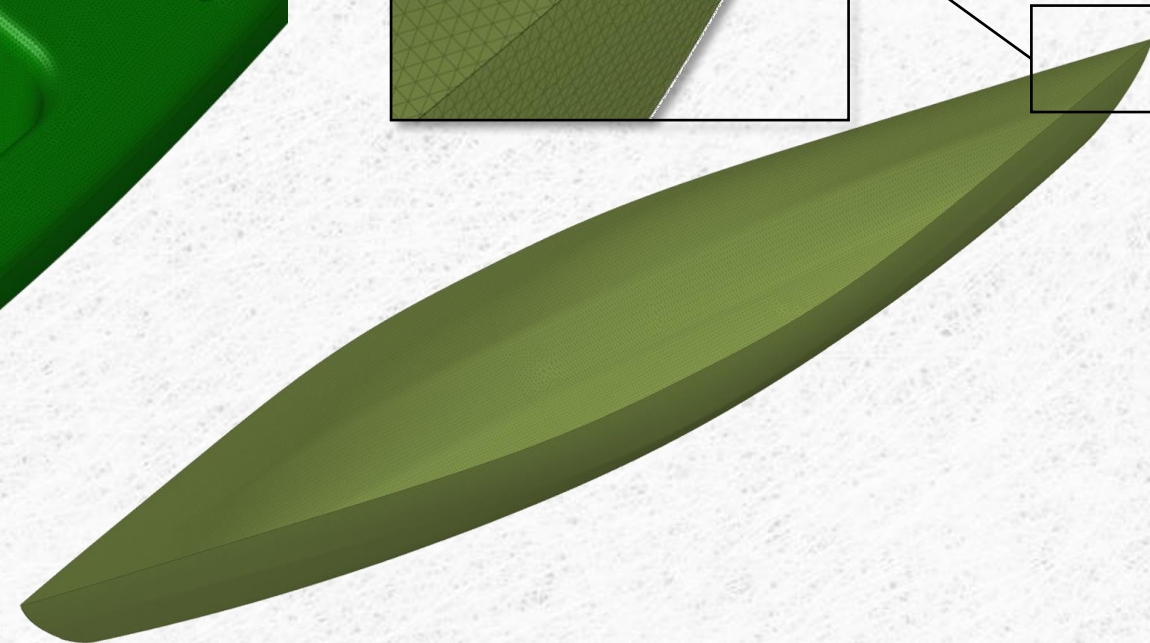
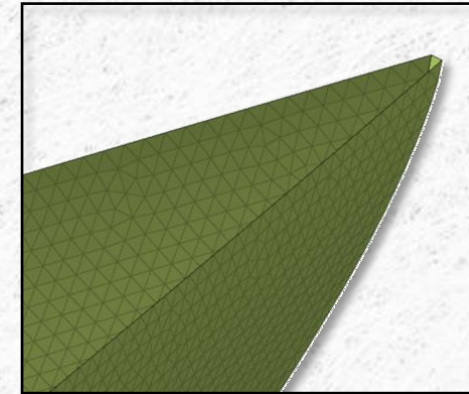
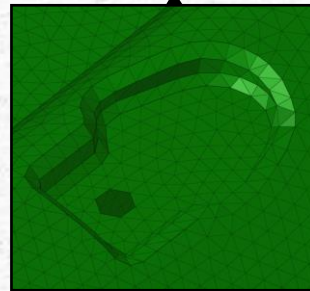
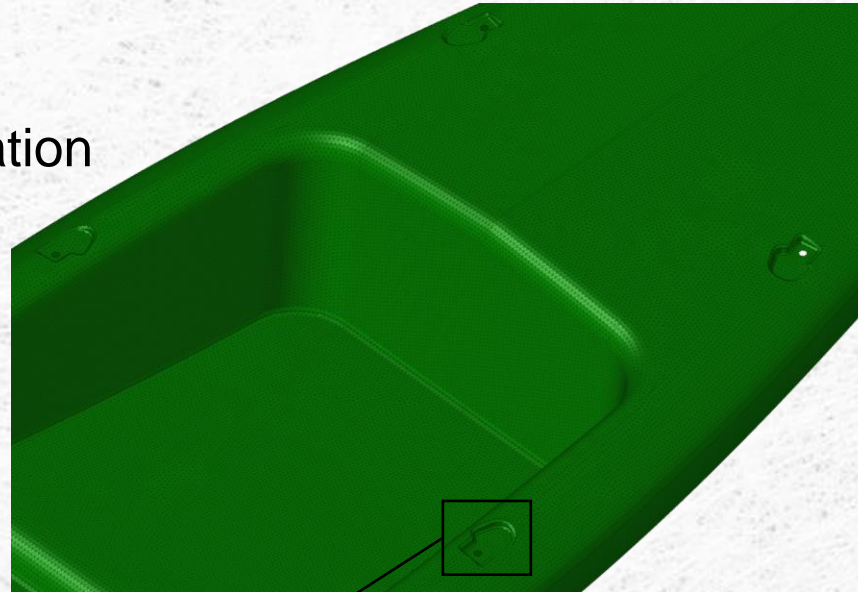
### Meshing - MC4 Specific Application

#### ELEMENT TYPES

- ▶ Kayak: 2D shell elements (triangular shape)

#### ELEMENT SIZE

- ▶ Kayak top side: 5 mm
- ▶ Kayak bottom side: 10 mm
- ▶ Correlation plate: 10 mm



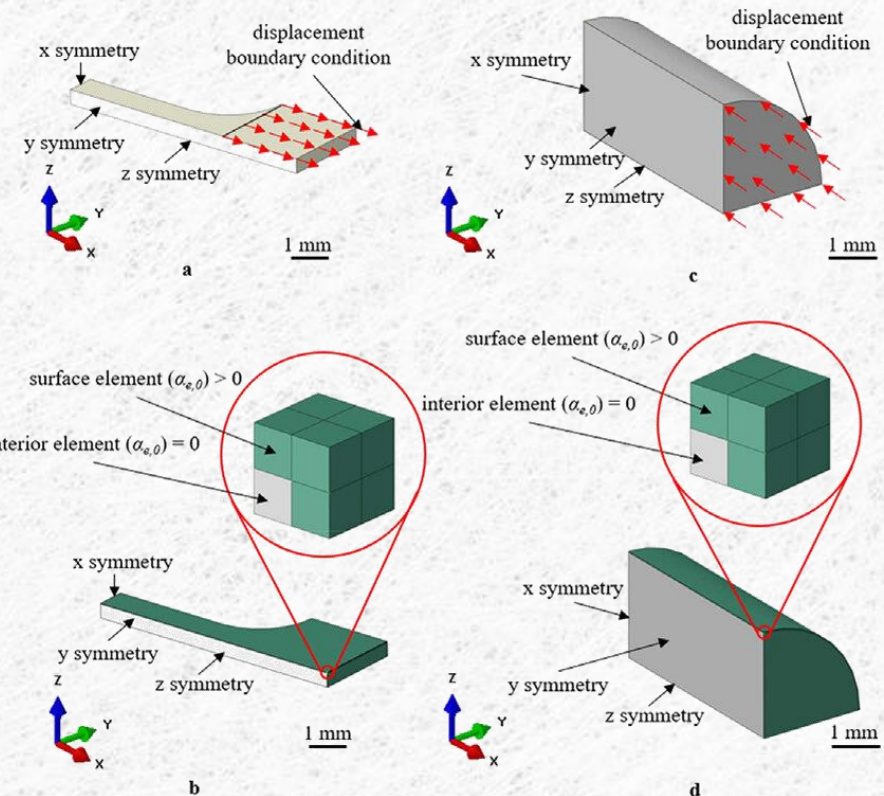
## Common sub-steps

### Model set-up:

The model setup process in Finite Element Analysis (FEA) involves several key steps to ensure that the simulation accurately represents the physical problem being analyzed. Here's an overview of the process:

- Consistence with the system of units
- Material properties assignment
- Boundary conditions application
- Loading conditions application
- Contact definition
- Solver settings configuration
- Pre-analysis checks

	(a)	(b)	(c)
Length unit	meter	millimeter	millimeter
Time unit	second	second	millisecond
Mass unit	kilogram	tonne	kilogram
Force unit	Newton	Newton	kiloNewton
Young's Modulus of Steel	210.0E+09	210.0E+03	210.0
Density of Steel	7.85E+03	7.85E-09	7.85E-06
Yield stress of Mild Steel	200.0E+06	200.0	0.200
Acceleration due to gravity	9.81	9.81E+03	9.81E-03
Velocity equivalent to 30 mph	13.4	13.4E+03	13.4

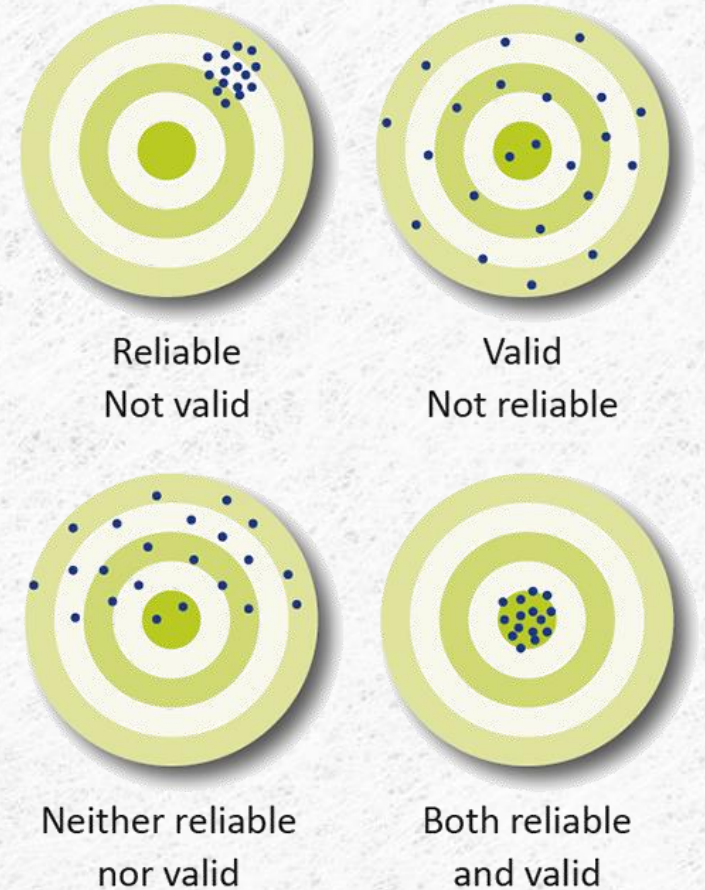


## Common sub-steps

### Analysis:

The analysis process in Finite Element Analysis (FEA) involves several steps to ensure that the simulation accurately predicts the behavior of the model under various conditions. Here's a detailed overview:

- Solving
- Iteration
- Validation

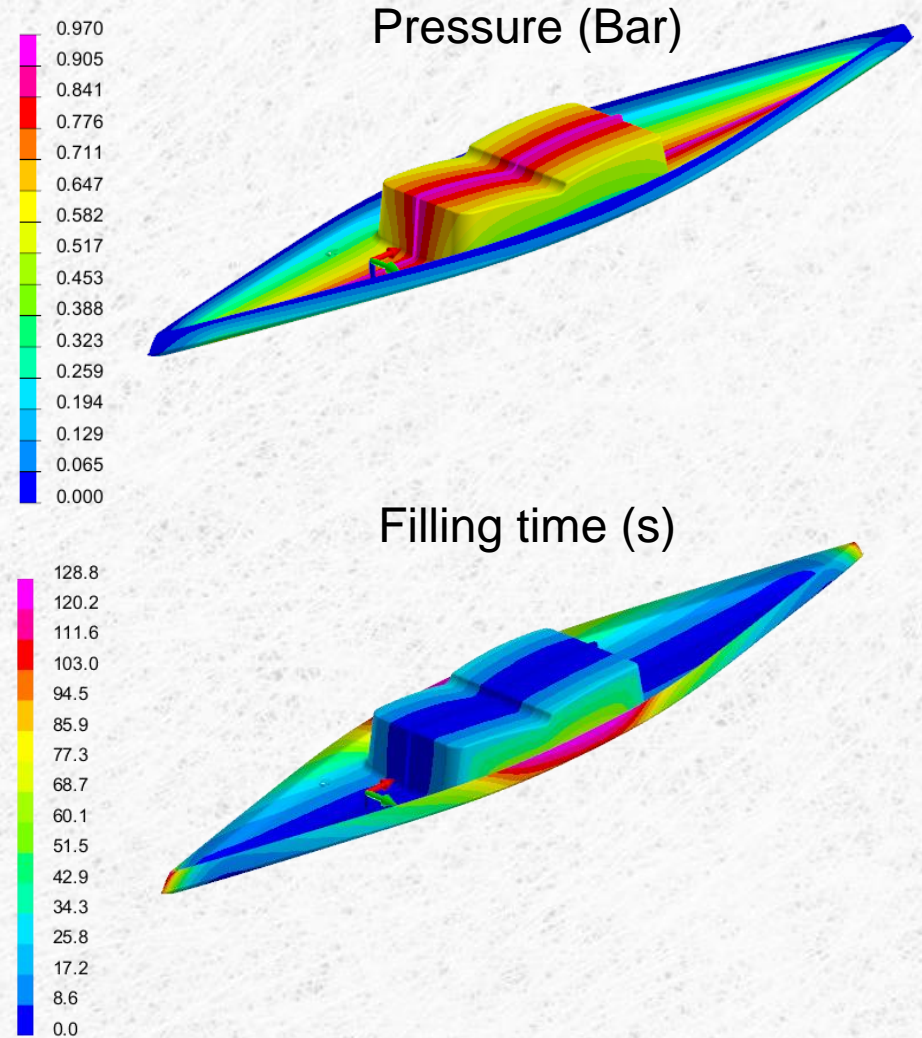


## Common sub-steps

### Report results:

The reporting results process in Finite Element Analysis (FEA) involves compiling and presenting the findings from the analysis in a clear and comprehensive manner. The main sub-steps are:

- Summary of objectives
- Model description
- Analysis set-up description
- Results presentation and interpretation
- Conclusions and recommendations

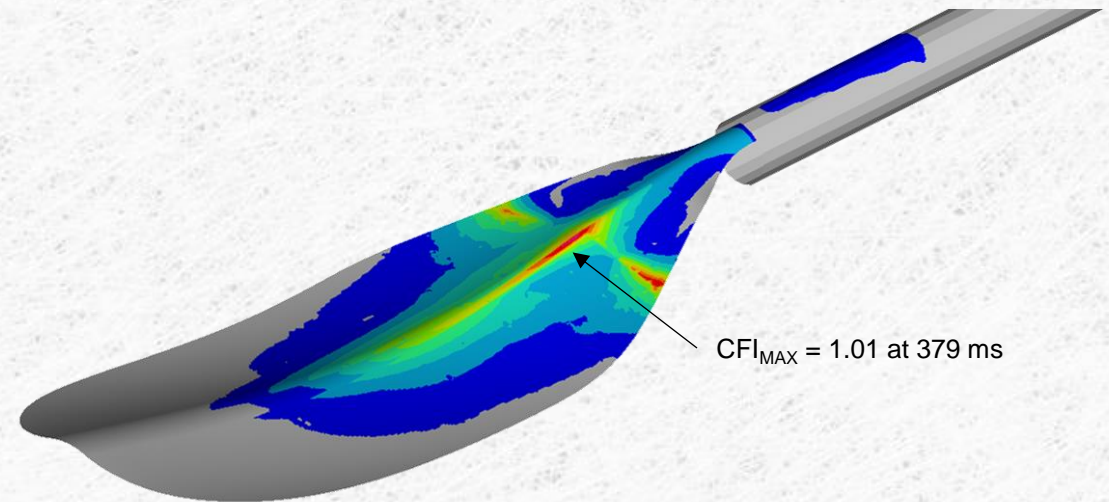
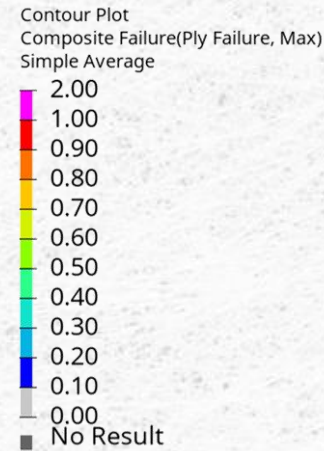
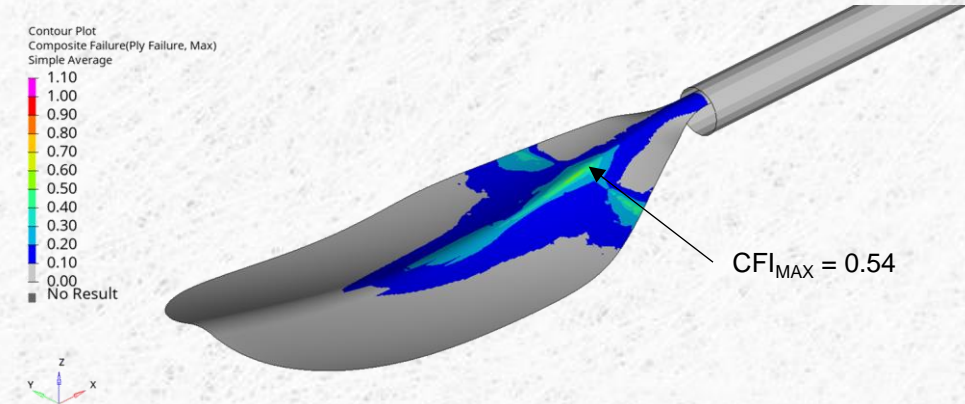


## Common sub-steps

### Report results:

Composite laminates failure theories are essential for predicting how and when composite materials will fail under various loading conditions. It is expressed in a range between 0 and 1, where 0 means no structural damage and 1 means failure. Some of the most used theories are:

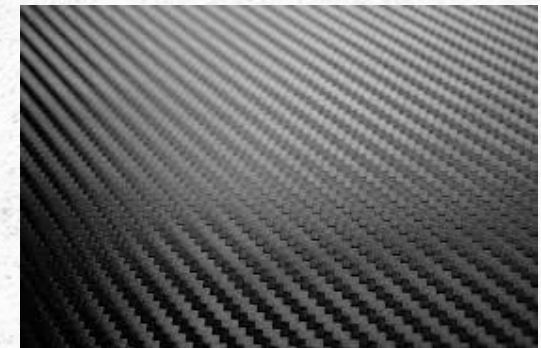
- Maximum stress theory
- Maximum strain theory
- Tsau-Wu failure criterion
- Tsau-Hill failure criterion
- Hoffman criterion
- Hashin-Rotem criterion



## Material definition

### Types:

- **Isotropic materials:** These materials have identical properties in all directions. This means their mechanical and thermal properties, such as elasticity, thermal conductivity, and strength, are the same regardless of the direction in which they are measured. Examples include most metals and glass.
- **Orthotropic materials:** These materials have different properties in three mutually perpendicular directions. Each direction has its own set of properties, making them directionally dependent but with a specific pattern. Common examples include wood and composite materials like carbon fiber-reinforced polymers.
- **Anisotropic materials:** These materials have properties that vary in all directions. Unlike isotropic and orthotropic materials, anisotropic materials do not have a uniform pattern of properties and can exhibit different behavior depending on the direction of measurement. Examples include certain crystals and many biological tissues.



## Material definition

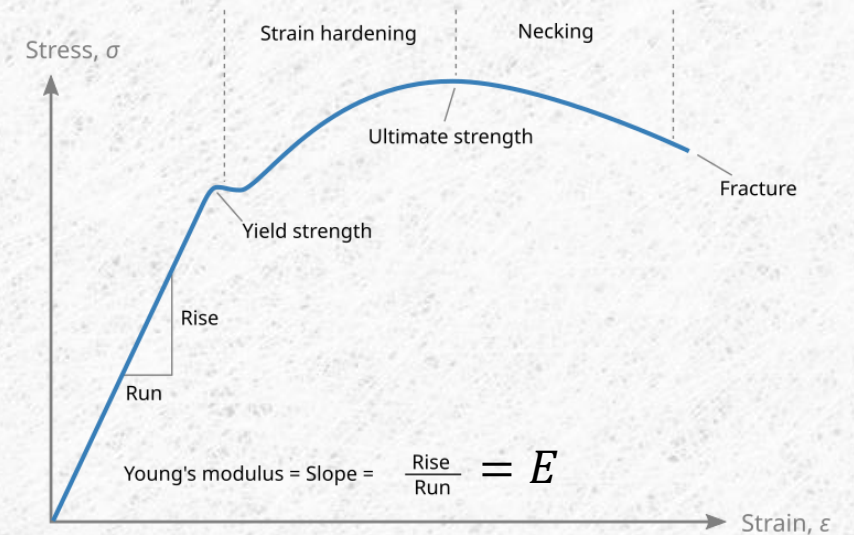
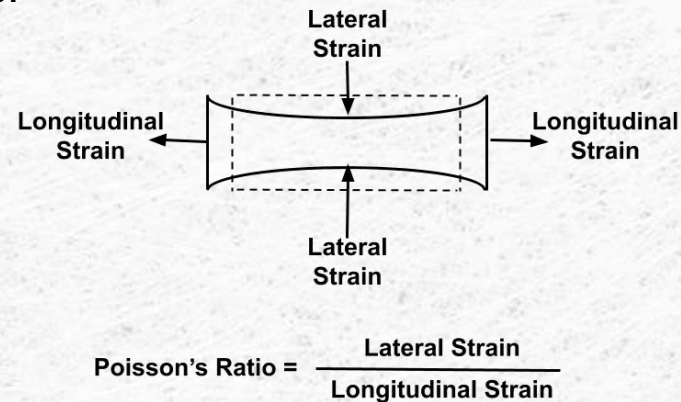
### Isotropic materials

Behavior defined by the following variables:

- $E$  is the Young's modulus
- $G$  is the shear modulus
- $\nu$  is the Poisson's ration

$$G = \frac{E}{2(1 + \nu)}$$

$$\sigma = E\varepsilon$$



## Material definition

### Orthotropic materials

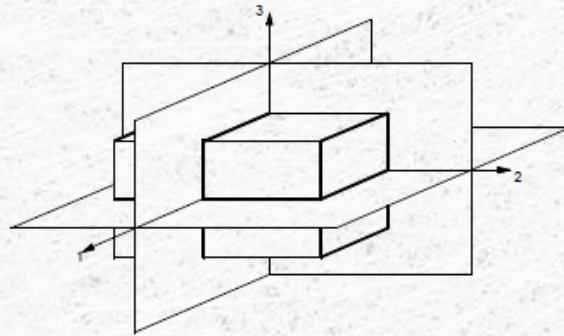
Behavior defined by the following variables:

- $E_1, E_2$  and  $E_3$  are the Young's modulus
- $G_{12}, G_{31}$  and  $G_{23}$  are the shear modulus
- $\nu_{12}, \nu_{31}$  and  $\nu_{23}$  are the Poisson's ration

Typical material with unidirectional fiber.

By symmetry:

$$\frac{\nu_{12}}{E_1} = \frac{\nu_{21}}{E_2}; \quad \frac{\nu_{13}}{E_1} = \frac{\nu_{31}}{E_3}; \quad \frac{\nu_{23}}{E_2} = \frac{\nu_{32}}{E_3}$$



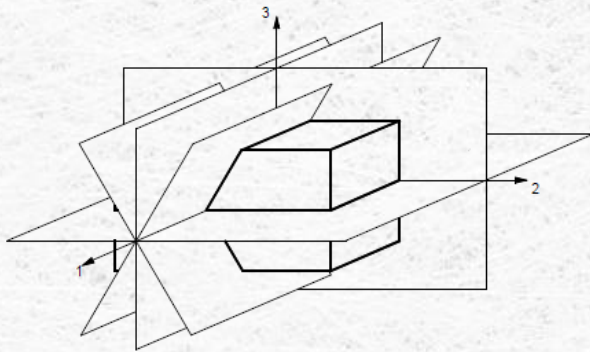
$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix}$$

## Material definition

### Orthotropic materials – Transversally isotropic

Behavior defined by the following variables:

- $E_1$  and  $E_2 = E_3$  are the Young's modulus
- $G_{12} = G_{31}$  and  $G_{23}$  are the shear modulus
- $\nu_{12} = \nu_{31}$  and  $\nu_{23}$  are the Poisson's ration



$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{21}}{E_2} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{2(1+\nu_{32})}{E_2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{12}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix}$$

## Properties definition

Depending on the used software, the properties are defined in many ways.

As an example, for OptiStruct solver, the main properties that must be defined are:

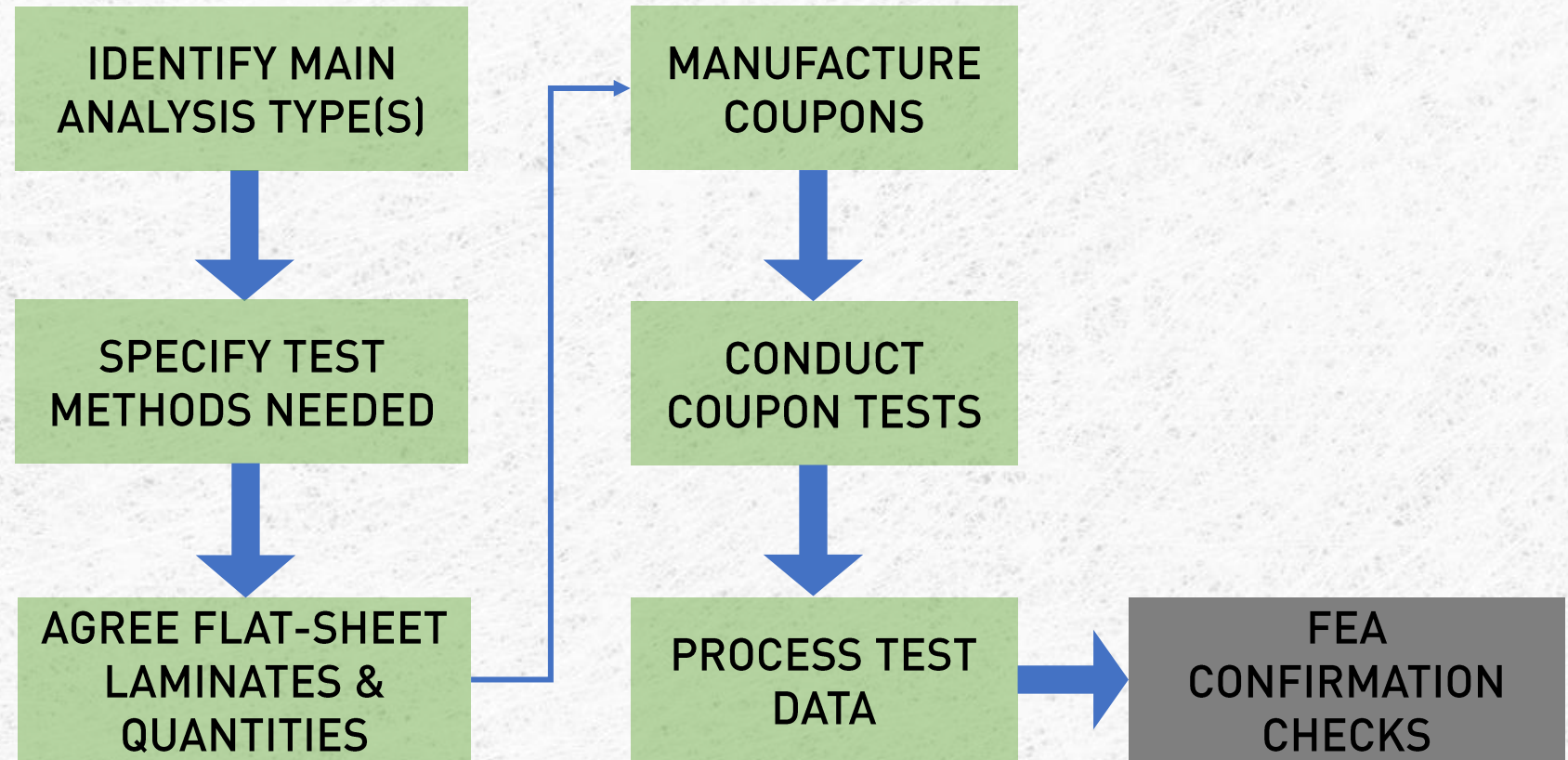
- Mechanical properties (Young's modulus, Poisson's ratio...)
- Strength properties (tensile, compression, shear strength...)

- Shell thickness
- Shell offset
- Number of plies

	Optistruct			
	Material		Property	
	2D elements	3D elements	2D elements	3D elements
Isotropic	MAT1	MAT1	PSHELL	PSOLID
Orthotropic	MAT8	MAT9OR	PCOMPP	PCOMPLS
Anisotropic	MAT2	MAT9	PCOMPP	PCOMPLS

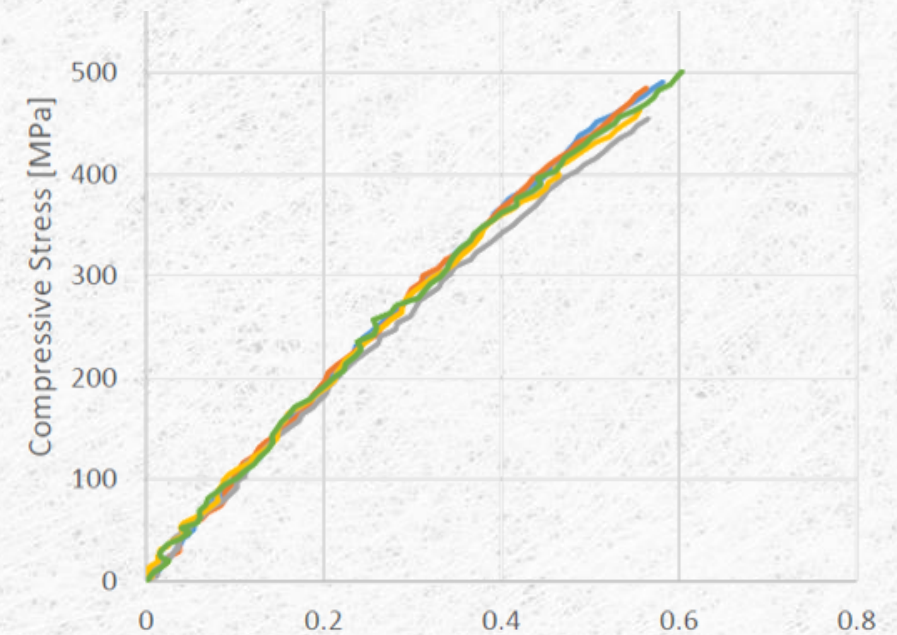
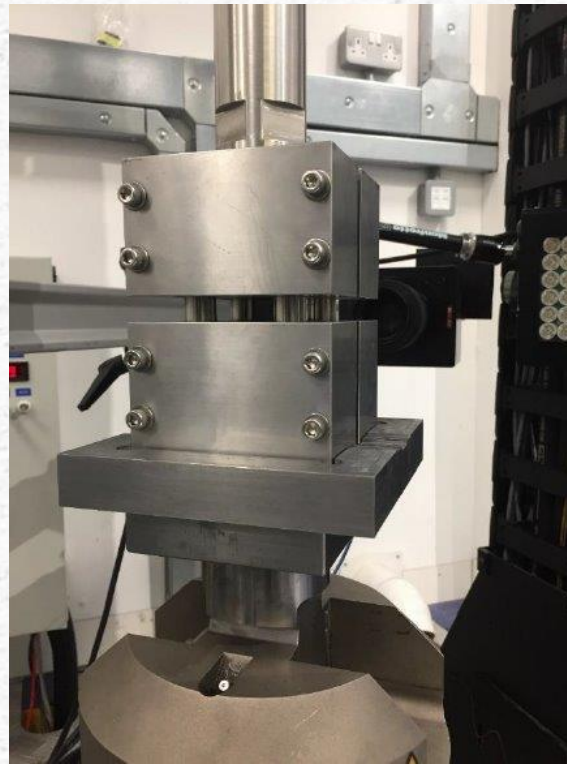
## Properties definition

Mechanical properties characterization



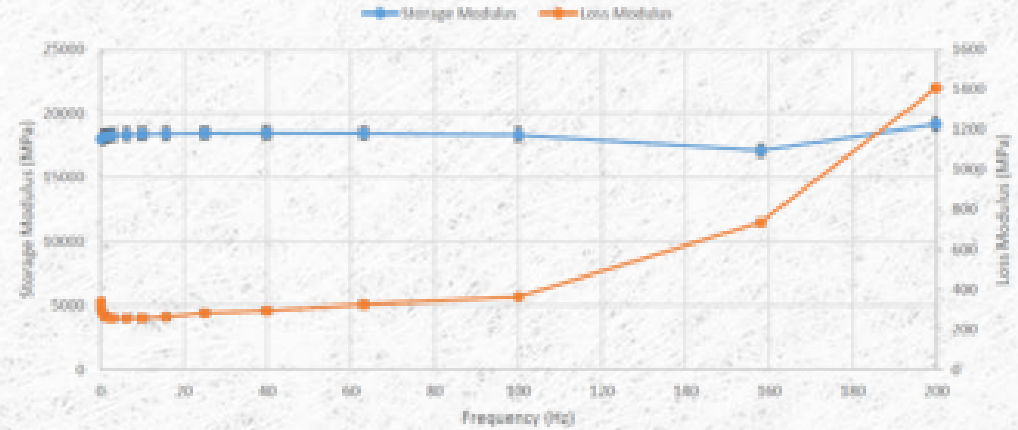
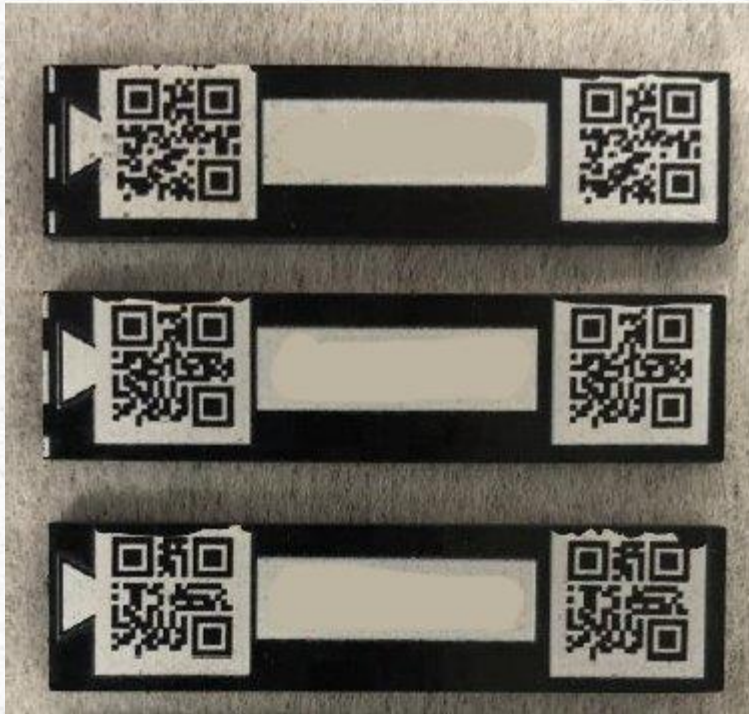
## Properties definition

### Compression test



## Properties definition

### Damping

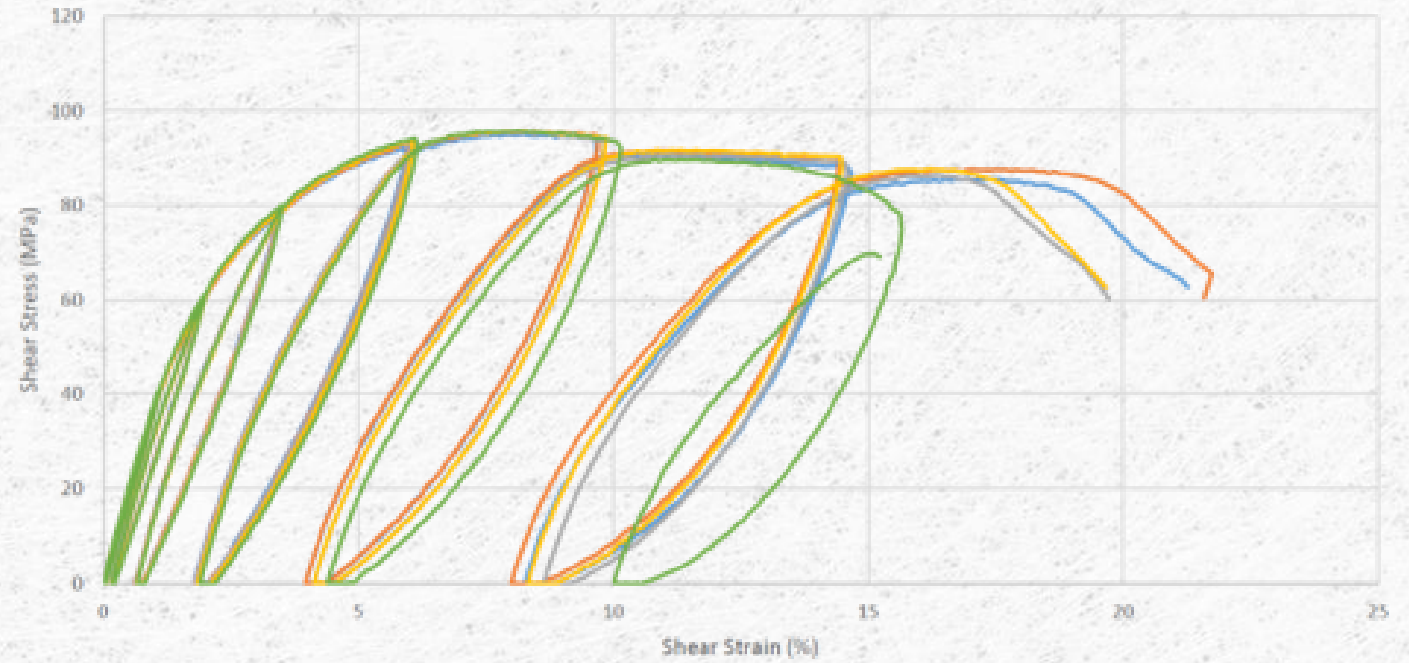
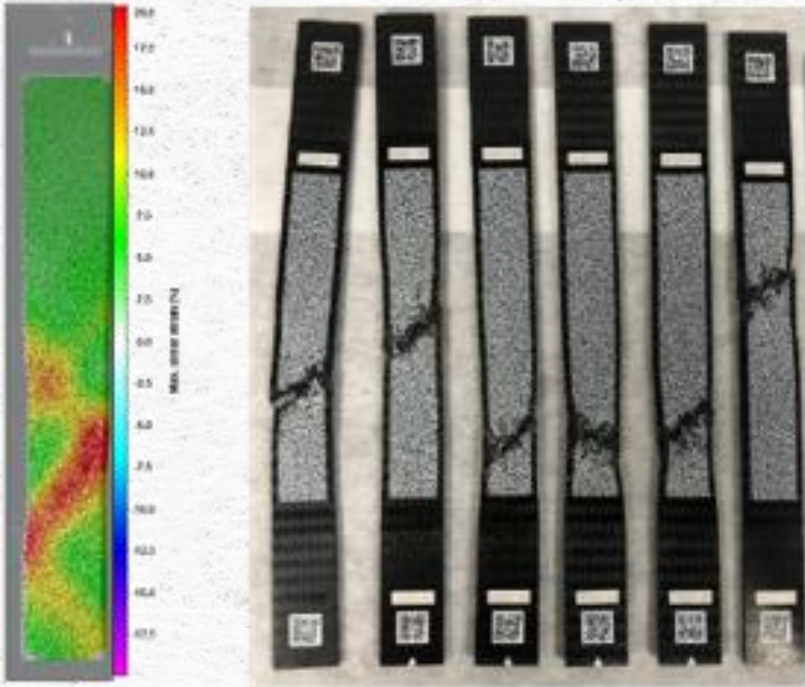


**Clamp width: 6.5 mm**  
**Clamp separation: 17 mm**  
*Coupon oscillated by vertical movement of central clamp. Frequency of oscillation varied from 0.1 Hz to 200 Hz. Storage and loss modulus recorded for 18 different frequencies over the range.*



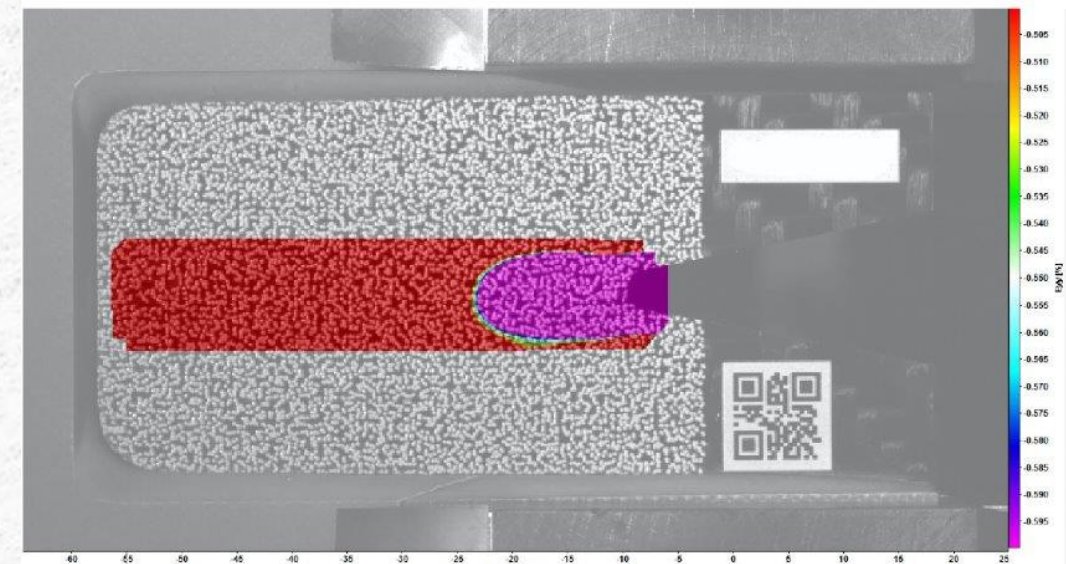
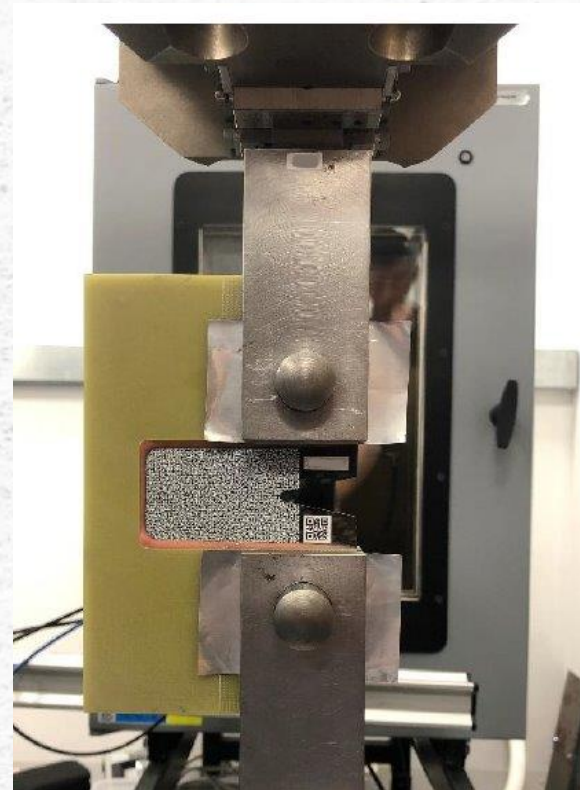
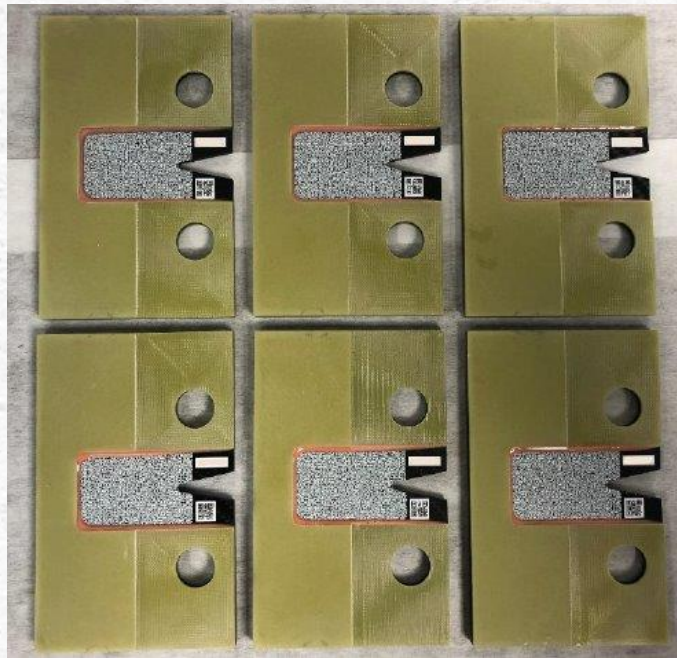
## Properties definition

Cyclic shear



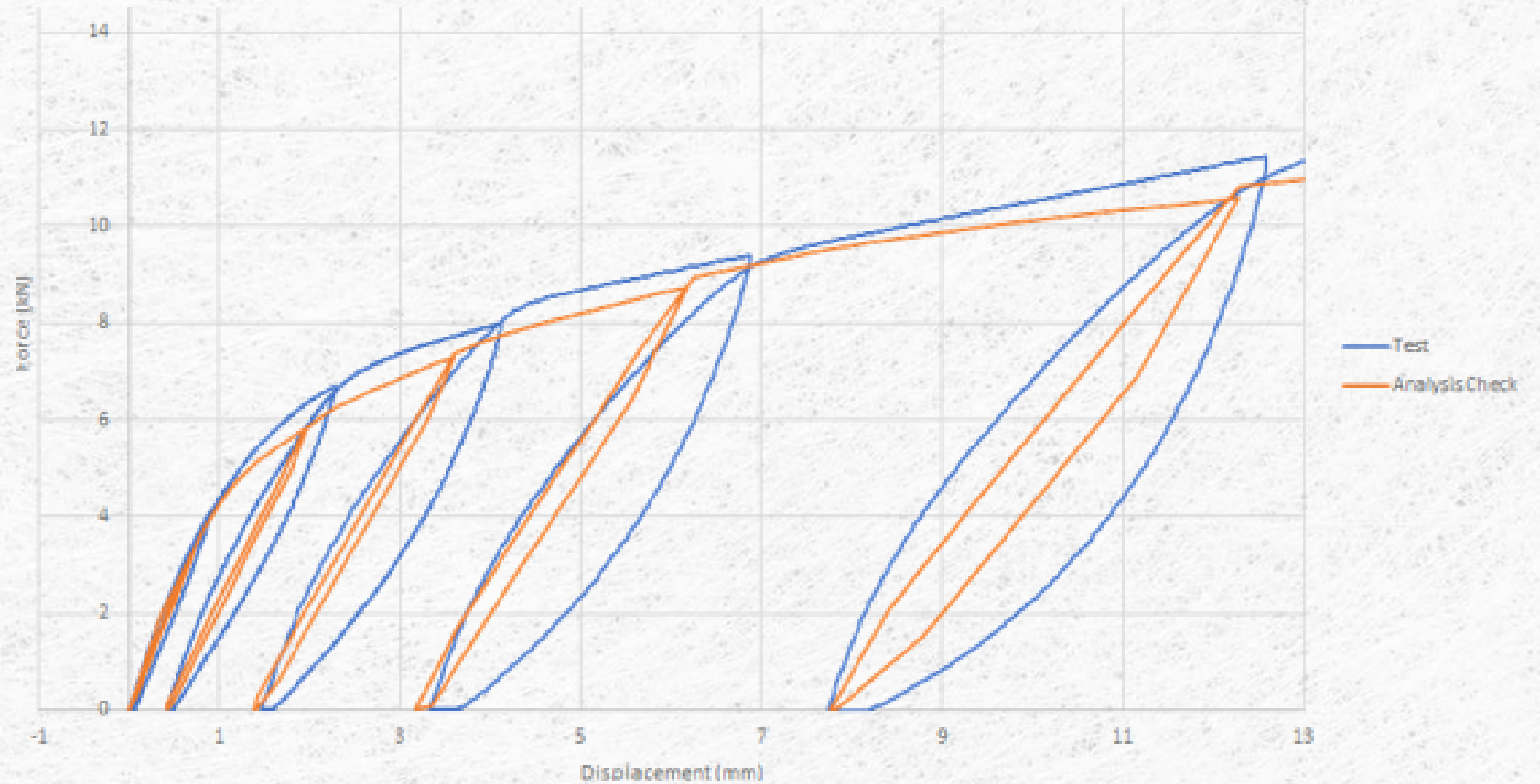
## Properties definition

### Fracture toughness



## Properties definition

Validation



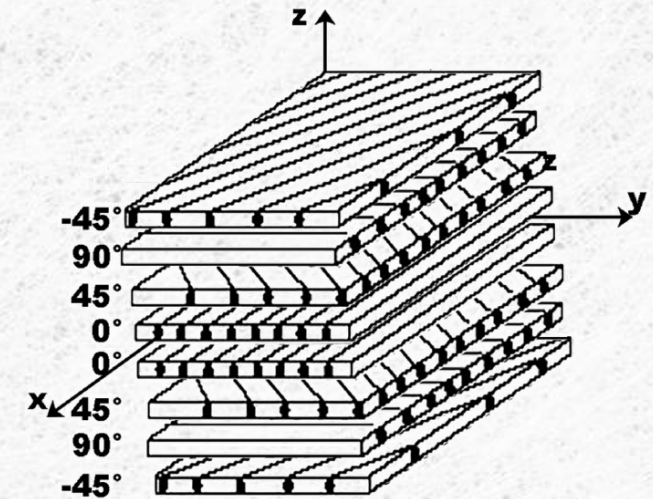
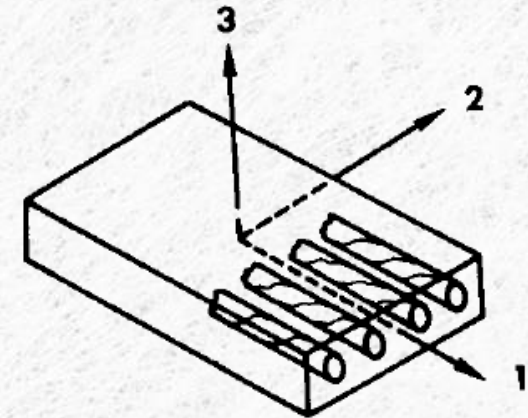
## Material reference orientation

Material reference orientation defines the alignment of the material's principal directions (usually the fiber directions in composites) relative to a global coordinate system. This orientation affects the material's stiffness, strength, and overall behavior under load.

The principal directions are these along which the material properties are defined. For composites, this typically are:

- 1 is the fiber direction
- 2 is the fiber transversal direction
- 3 is the fiber transversal and out of the plane direction

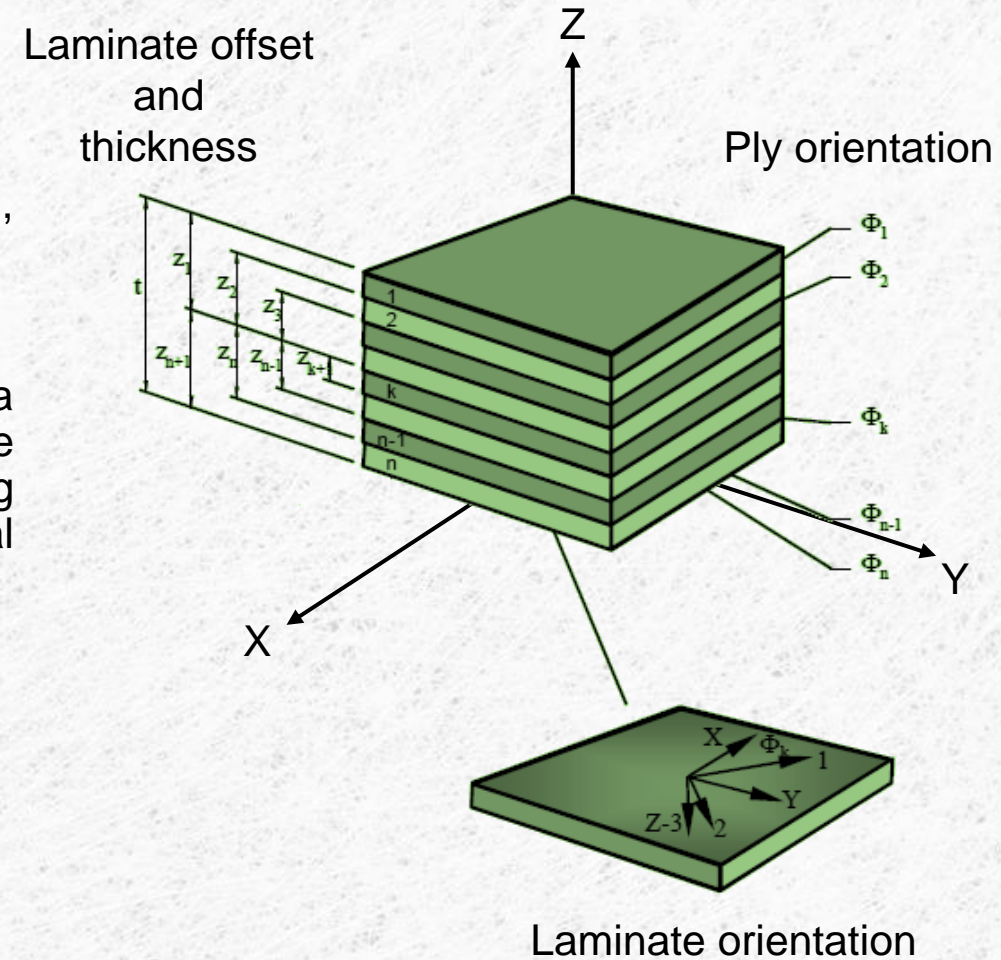
Also, the angle method is used, which specifies the rotation angle of the material's principal direction relative to the global coordinate system.



## Laminate definition

A laminate is a set of plies, with a dimension much smaller than the other two, placed on top of each other and joined together.

The individual layers, or plies, consist of high-strength fibers embedded in a matrix material. Common fibers used include carbon, glass, and aramid, while typical matrix materials are polymers like epoxy. The orientation and stacking sequence of these layers significantly influence the overall mechanical properties of the laminate



## Laminate definition – Stress calculations

The relationship between stress and strain in plane stress for non-oriented axes is:

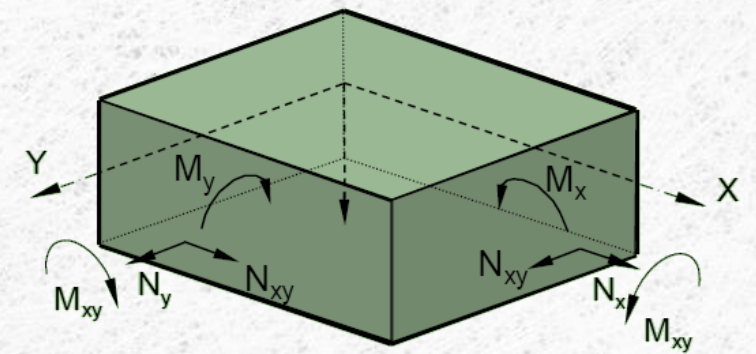
$$\{\bar{\sigma}\} = [\bar{Q}] \{\bar{\varepsilon}\} = [\bar{Q}] (\{\varepsilon^0\} + z \{K\})$$

To obtain the equilibrium equations, it is integrated with respect to the thickness  $t$  of the laminate.

Where:

- $N$  is the in-plane load
- $M$  is the bending moment
- $[Q]$  is the laminate stiffness matrix
- $\{K\}$  is the mid-plane curvature vector

$$\begin{aligned} N_x &= \int_{-t/2}^{t/2} \sigma_x dz & M_x &= \int_{-t/2}^{t/2} \sigma_x z dz \\ N_y &= \int_{-t/2}^{t/2} \sigma_y dz & M_y &= \int_{-t/2}^{t/2} \sigma_y z dz \\ N_{xy} &= \int_{-t/2}^{t/2} \tau_{xy} dz & M_{xy} &= \int_{-t/2}^{t/2} \tau_{xy} z dz \end{aligned}$$



## Laminate definition – Stress calculations

Mathematically developing the above equation, we obtain:

$$\begin{Bmatrix} N_X \\ N_Y \\ N_Z \\ M_X \\ M_Y \\ M_Z \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \\ B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \\ D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_X^0 \\ \varepsilon_Y^0 \\ \gamma_{XY}^0 \\ K_X \\ K_Y \\ K_{XY} \end{Bmatrix} = \begin{bmatrix} [A] & [B] \\ [B] & [D] \end{bmatrix} \begin{Bmatrix} \varepsilon^0 \\ K \end{Bmatrix}$$

[A] is the in-plane stiffness matrix

[B] is stiffness coupling matrix

[D] is the torsional and bending matrix

## Laminate definition – Stress calculations

If the [B] matrix is not null, there are couplings between stresses and deformations in the plane and curvature. Usually, this coupling effect it is not desirable.

To avoid it, symmetric laminates must be use.

$$B_{ij} = \sum_{k=1}^n \left[ (\bar{Q}_{ij})_k \int_{z_k}^{z_{k+1}} z \, dz \right] = \frac{1}{2} \sum_{k=1}^n \left[ (\bar{Q}_{ij})_k (z_{k+1}^2 - z_k^2) \right]$$

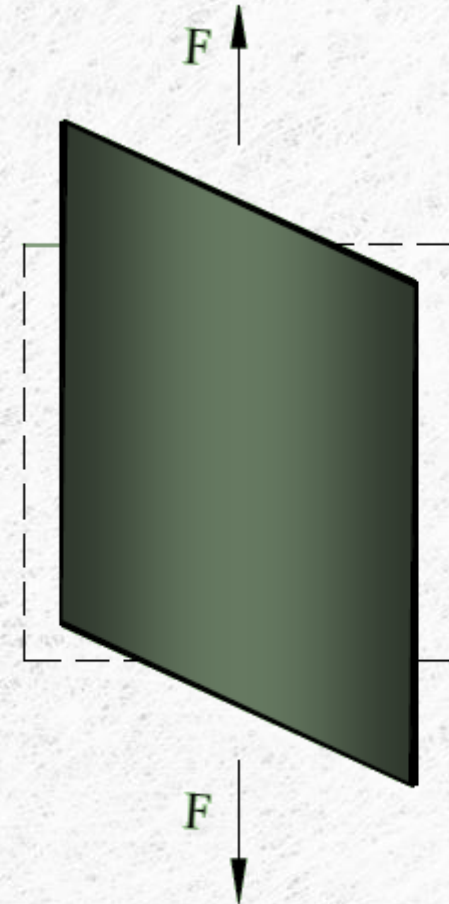


## Laminate definition – Stress calculations

If the terms  $A_{16}$  and  $A_{26}$  are no zero, there are couplings between the normal and tangential stresses and deformations, all of them in the plane. Usually, this coupling effect it is not desirable.

It can be avoided by using balanced laminates, unidirectional oriented or crusaders.

$$A_{ij} = \sum_{k=1}^n \left[ (\bar{Q}_{ij})_k \int_{z_k}^{z_{k+1}} dz \right] = \sum_{k=1}^n [(\bar{Q}_{ij})_k (z_{k+1} - z_k)]$$



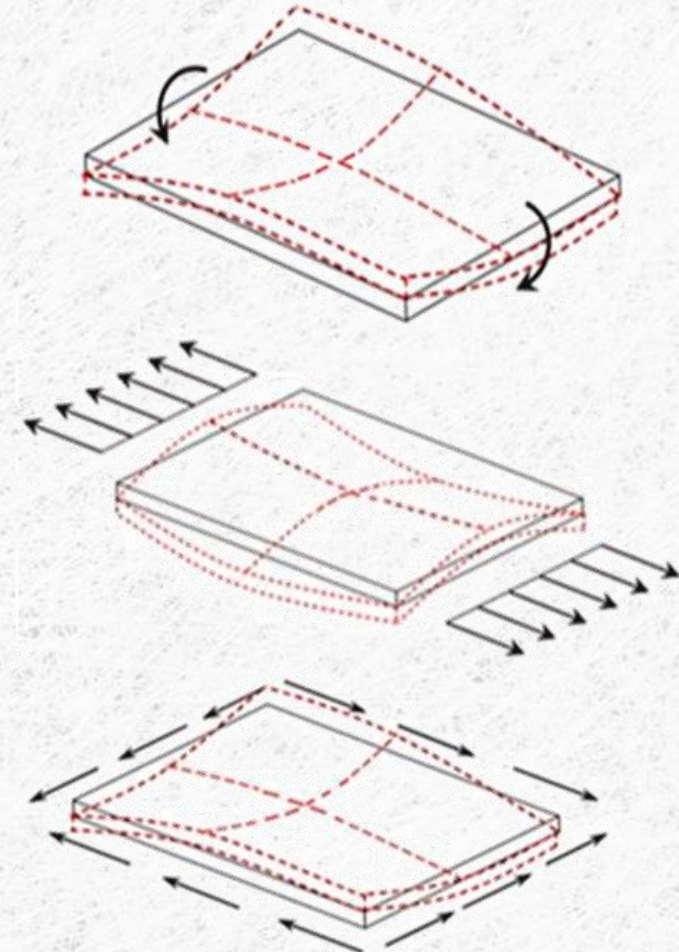
## Laminate definition – Stress calculations

If the terms  $D_{16}$  and  $D_{26}$  are no zero, there are couplings between the bending and torsional curvature. As the previous effects, usually it is not desirable.

It can be avoided by using anti-symmetrical laminates, unidirectional or crossed.

In symmetrical and balanced laminates, it cannot be eliminated. It is minimized by placing the sheets with  $\Phi$  and  $-\Phi$  orientations as close as possible and by increasing the number of sheets.

$$D_{ij} = \sum_{k=1}^n \left[ (\bar{Q}_{ij})_k \int_{z_k}^{z_{k+1}} z^2 dz \right] = \frac{1}{3} \sum_{k=1}^n \left[ (\bar{Q}_{ij})_k (z_{k+1}^3 - z_k^3) \right]$$



## Laminate theory checks

Laminates types:

Laminates	Balanced	Symmetrical	Anti-symmetrical	Crossed
[A]	$\begin{bmatrix} A_{11} & A_{12} & 0 \\ A_{12} & A_{22} & 0 \\ 0 & 0 & A_{66} \end{bmatrix}$	$\begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix}$	$\begin{bmatrix} A_{11} & A_{12} & 0 \\ A_{12} & A_{22} & 0 \\ 0 & 0 & A_{66} \end{bmatrix}$	$\begin{bmatrix} A_{11} & A_{12} & 0 \\ A_{12} & A_{22} & 0 \\ 0 & 0 & A_{66} \end{bmatrix}$
[B]	$\begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & B_{16} \\ 0 & 0 & B_{26} \\ B_{16} & B_{26} & 0 \end{bmatrix}$	$\begin{bmatrix} B_{11} & 0 & 0 \\ 0 & -B_{11} & 0 \\ 0 & 0 & 0 \end{bmatrix}$
[D]	$\begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix}$	$\begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix}$	$\begin{bmatrix} D_{11} & D_{12} & 0 \\ D_{12} & D_{22} & 0 \\ 0 & 0 & D_{66} \end{bmatrix}$	$\begin{bmatrix} D_{11} & D_{12} & 0 \\ D_{12} & D_{22} & 0 \\ 0 & 0 & D_{66} \end{bmatrix}$

## Laminate theory checks

Laminates types:

	Balanced	Symmetrical	Anti-symmetrical	Crossed
Laminates examples	[0/45/-45] [+30/-30]	[0/45/-30/-30/45/0] [0/45/90/90/45/0]	[45/-45/0/90/0/45/-45]	[0/0/90/0/90/90]

- Balanced: for each ply with orientation  $\theta$ , it is another ply (same thickness and composition) with orientation  $-\theta$
- Symmetrical: for each ply with orientation  $\theta$  and a  $z_i$  distant with respect to the midplane of the laminate, must be another ply (same thickness, composition and orientation) at a distance of  $-z_i$
- Anti-symmetrical: for each ply with orientation  $\theta$  and a  $z_i$  distant with respect to the midplane of the laminate, must be another ply (same thickness and composition) with orientation  $-\theta$  and at a distance of  $-z_i$
- Crossed: all the layers (plies) are oriented at  $0^\circ$  and  $90^\circ$  angles

## Laminate theory checks

Laminates types:

Laminates	Quasi-orthotropic (symmetrical and balanced)	Orthotropic (symmetrical and crossed)	Quasi-isotropic (symmetrical, balanced and same thickness)	Isotropic (non-symmetrical)	Isotropic (symmetrical)
[A]	$\begin{bmatrix} A_{11} & A_{12} & 0 \\ A_{12} & A_{22} & 0 \\ 0 & 0 & A_{66} \end{bmatrix}$	$\begin{bmatrix} A_{11} & A_{12} & 0 \\ A_{12} & A_{22} & 0 \\ 0 & 0 & A_{66} \end{bmatrix}$	$\begin{bmatrix} A_{11} & A_{12} & 0 \\ A_{12} & A_{22} & 0 \\ 0 & 0 & \frac{A_{11} - A_{12}}{2} \end{bmatrix}$	$\begin{bmatrix} A_{11} & A_{12} & 0 \\ A_{12} & A_{22} & 0 \\ 0 & 0 & \frac{A_{11} - A_{12}}{2} \end{bmatrix}$	$\begin{bmatrix} A_{11} & A_{12} & 0 \\ A_{12} & A_{22} & 0 \\ 0 & 0 & \frac{A_{11} - A_{12}}{2} \end{bmatrix}$
[B]	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} B_{11} & B_{12} & 0 \\ B_{12} & B_{11} & 0 \\ 0 & 0 & \frac{B_{11} - B_{12}}{2} \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$
[D]	$\begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix}$	$\begin{bmatrix} D_{11} & D_{12} & 0 \\ D_{12} & D_{22} & 0 \\ 0 & 0 & D_{66} \end{bmatrix}$	$\begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix}$	$\begin{bmatrix} D_{11} & D_{12} & 0 \\ D_{12} & D_{22} & 0 \\ 0 & 0 & \frac{D_{11} - D_{12}}{2} \end{bmatrix}$	$\begin{bmatrix} D_{11} & D_{12} & 0 \\ D_{12} & D_{22} & 0 \\ 0 & 0 & \frac{D_{11} - D_{12}}{2} \end{bmatrix}$

## Laminate theory - Nomenclature

Laminate nomenclature is a standardized way to describe the stacking sequence and orientation of plies in a composite laminate.

The key elements are:

### 1. Ply orientation

- Each ply (layer) is labeled by its fiber orientation angle relative to a reference direction, typically the  $0^\circ$  axis.
- Common orientations include  $0^\circ$ ,  $90^\circ$ ,  $+45^\circ$ , and  $-45^\circ$ .

### 2. Stacking sequence

- The sequence in which the plies are stacked is listed from the bottom to the top of the laminate.
- Each ply is separated by a slash /

### 3. Symmetry

- Symmetric laminates have a mirror image arrangement of plies above and below the mid-plane.
- Denotated with a subscript S  $[0/90/45/-45]_S$

## Laminate theory - Nomenclature

Laminate nomenclature is a standardized way to describe the stacking sequence and orientation of plies in a composite laminate.

The key elements are:

### 4. Balanced laminates

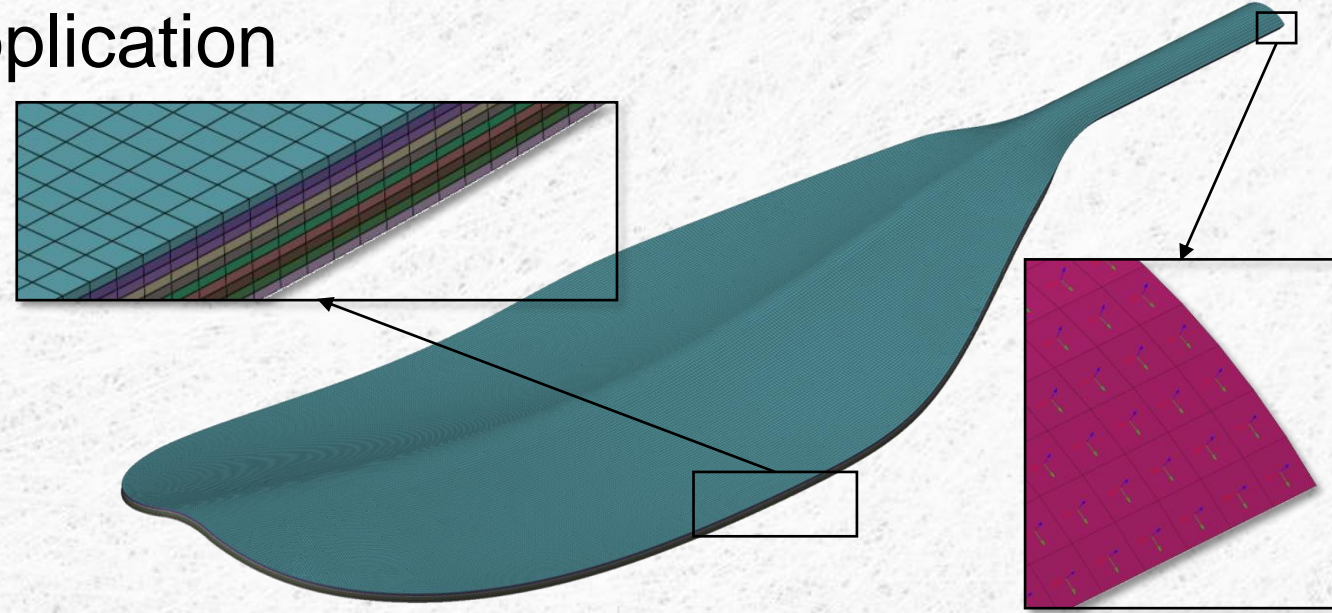
- A laminate is balanced if it has equal numbers of + and - angled plies.
- As is explained before, this ensures that the laminate does not exhibit coupling between bending and twisting.

### 5. Repetition and grouping

- Repeating groups of plies within a laminate can be enclosed in parentheses.
- For example,  $[0/90]_2$  indicates two sets of  $0^\circ$  and  $90^\circ$  plies

## Laminate theory - MC4 Specific Application

PLY	Pre-preg type	Direction	Paddle
<b>MOULD</b>			
1	G-Weave 360P_ MC4-F21 0.32T	0/90°	X
2	G-Weave 360P_ MC4-F21 0.32T	±45°	X
3	G-Weave 360P_ MC4-F21 0.32T	0/90°	X
4	G-Weave 360P_ MC4-F21 0.32T	±45°	X
5	G-Weave 360P_ MC4-F21 0.32T	0/90°	X
6	G-Weave 360P_ MC4-F21 0.32T	0/90°	X
7	G-Weave 360P_ MC4-F21 0.32T	±45°	X
8	G-Weave 360P_ MC4-F21 0.32T	0/90°	X
9	G-Weave 360P_ MC4-F21 0.32T	±45°	X
10	G-Weave 360P_ MC4-F21 0.32T	0/90°	X
<b>TOTAL THICKNESS</b>		<b>mm</b>	<b>3.2</b>



Engineering constants							Laminate Matrices						
	$E_x$	$E_y$	$E_z$	$G_{xy}$	$G_{xz}$	$G_{yz}$							
In-plane	+1.831E+04	+2.140E+04		+5.602E+03									
Bending	+1.878E+04	+2.218E+04		+5.322E+03									
Zero-Curvature	+1.831E+04	+2.140E+04		+5.602E+03									
	$\nu_{xy}$	$\nu_{yx}$	$\nu_{xz}$	$\nu_{zx}$	$\nu_{yz}$	$\nu_{zy}$							
In-plane	+0.426	+0.498											
Bending	+0.409	+0.484											
Zero-Curvature	+0.426	+0.498											
							<b>[ABD] Matrix</b>						
$N_x$	+7.462E+04	+3.730E+04	-2.095E+03	+3.092E-11	+1.091E-11	-7.958E-13	$\epsilon_x^0$						
$N_y$	+3.730E+04	+8.719E+04	-2.095E+03	+1.091E-11	+2.910E-11	-7.958E-13	$\epsilon_y^0$						
$N_{xy}$	-2.095E+03	-2.095E+03	+1.800E+04	-7.958E-13	-7.958E-13	+5.230E-12	$\gamma_{xy}^0$						
$M_x$	+3.092E-11	+1.091E-11	-7.958E-13	+6.402E+04	+3.105E+04	-1.573E+03	$K_x$						
$M_y$	+1.091E-11	+2.910E-11	-7.958E-13	+3.105E+04	+7.561E+04	-1.573E+03	$K_y$						
$M_{xy}$	-7.958E-13	-7.958E-13	+5.230E-12	-1.573E+03	-1.573E+03	+1.458E+04	$K_{xy}$						
							<b>[ABD]<sup>-1</sup> Matrix</b>						
$\epsilon_x^0$	+1.707E-05	-7.275E-06	+1.140E-06	-8.947E-21	+4.014E-21	-4.065E-22	$N_x$						
$\epsilon_y^0$	-7.275E-06	+1.460E-05	+8.528E-07	+4.052E-21	-6.229E-21	-1.408E-22	$N_y$						
$\gamma_{xy}^0$	+1.140E-06	+8.528E-07	+5.578E-05	-4.213E-22	-1.480E-22	-1.996E-20	$N_{xy}$						
$K_x$	-8.947E-21	+4.014E-21	-4.065E-22	+1.953E-05	-7.992E-06	+1.244E-06	$M_x$						
$K_y$	+4.052E-21	-6.229E-21	-1.408E-22	-7.992E-06	+1.653E-05	+9.208E-07	$M_y$						
$K_{xy}$	-4.213E-22	-1.480E-22	-1.996E-20	+1.244E-06	+9.208E-07	+6.881E-05	$M_{xy}$						

## Laminate theory - MC4 Specific Application

PLY	Pre-preg type	Direction	Kayak	Reinforcement
MOULD				
1	G-Weave 360P_ MC4-F21 0.32T	0/90°	X	X
2	G-Weave 360P_ MC4-F21 0.32T	±45°	X	X
3	G-Weave 360P_ MC4-F21 0.32T	0/90°	X	X
4	G-Weave 360P_ MC4-F21 0.32T	±45°	X	X
5	G-Weave 360P_ MC4-F21 0.32T	0/90°	X	X
6	G-Weave 360P_ MC4-F21 0.32T	0/90°		X
7	G-Weave 360P_ MC4-F21 0.32T	±45°		X
8	G-Weave 360P_ MC4-F21 0.32T	0/90°		X
	TOTAL THICKNESS	mm	1.5	2.4

Engineering constants						
	$E_x$	$E_y$	$E_z$	$G_{xy}$	$G_{xz}$	$G_{yz}$
In-plane	+1.831E+04	+2.140E+04		+5.602E+03		
Bending	+2.001E+04	+2.437E+04		+4.479E+03		
Zero-Curvature	+1.831E+04	+2.140E+04		+5.602E+03		
	$\nu_{xy}$	$\nu_{yx}$	$\nu_{xz}$	$\nu_{zx}$	$\nu_{yz}$	$\nu_{zy}$
In-plane	+0.426	+0.498				
Bending	+0.362	+0.441				
Zero-Curvature	+0.426	+0.498				

Laminate Matrices							
[ABD] Matrix							
$N_x$	+3.731E+04	+1.865E+04	-1.048E+03	-9.095E-13	+2.274E-13	+2.842E-14	$\epsilon_x^0$
$N_y$	+1.865E+04	+4.359E+04	-1.048E+03	+2.274E-13	-9.095E-13	+2.842E-14	$\epsilon_y^0$
$N_{xy}$	-1.048E+03	-1.048E+03	+9.001E+03	+2.842E-14	+2.842E-14	-1.137E-13	$\gamma_{xy}^0$
$M_x$	-9.095E-13	+2.274E-13	+2.842E-14	+8.134E+03	+3.589E+03	-1.162E+02	$K_x$
$M_y$	+2.274E-13	-9.095E-13	+2.842E-14	+3.589E+03	+9.904E+03	-1.162E+02	$K_y$
$M_{xy}$	+2.842E-14	+2.842E-14	-1.137E-13	-1.162E+02	-1.162E+02	+1.531E+03	$K_{xy}$

[ABD] <sup>-1</sup> Matrix							
$\epsilon_x^0$	+3.414E-05	-1.455E-05	+2.280E-06	+6.135E-21	-4.350E-21	-5.891E-23	$N_x$
$\epsilon_y^0$	-1.455E-05	+2.920E-05	+1.706E-06	-4.498E-21	+4.640E-21	-1.347E-22	$N_y$
$\gamma_{xy}^0$	+2.280E-06	+1.706E-06	+1.116E-04	-1.499E-23	-1.142E-22	+8.200E-21	$N_{xy}$
$K_x$	+6.135E-21	-4.350E-21	-5.891E-23	+1.464E-04	-5.298E-05	+7.093E-06	$M_x$
$K_y$	-4.498E-21	+4.640E-21	-1.347E-22	-5.298E-05	+1.202E-04	+5.105E-06	$M_y$
$K_{xy}$	-1.499E-23	-1.142E-22	+8.200E-21	+7.093E-06	+5.105E-06	+6.541E-04	$M_{xy}$

# Process simulations

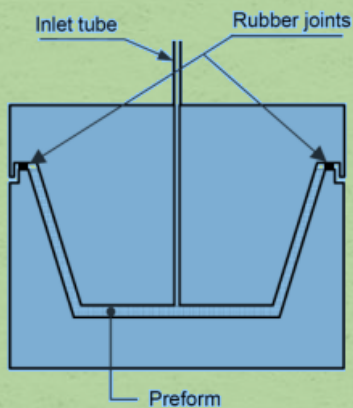


Funded by  
the European Union

## Liquid composite modeling

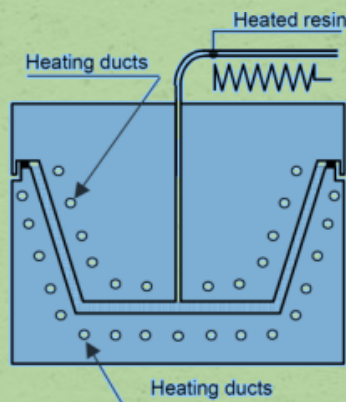
### Closed mold RTM

- No mold deformation
- Isothermal



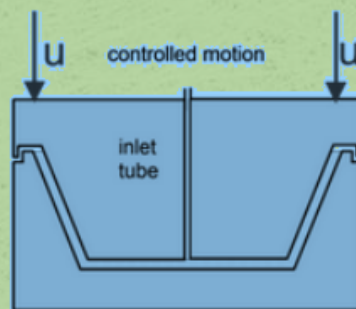
### Heated RTM

- Heating system of the mold
- Resin reaction during curing



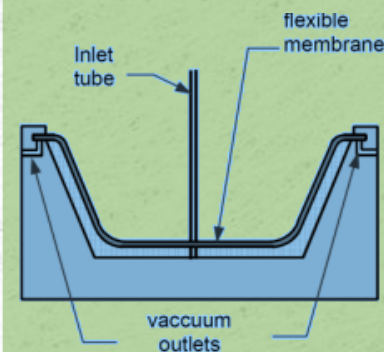
### Injection-compression (CRTM)

- Partial mold opening during resin injection
- Transverse flow negligible



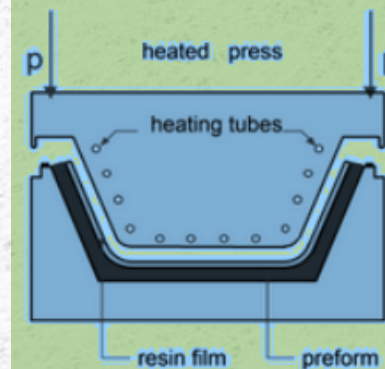
### Vacuum assisted resin infusion (VARI)

- Infusion of the resin under a flexible membrane
- Use of flow media



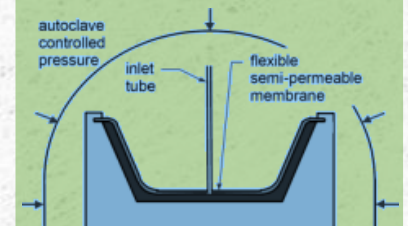
### Resin film infusion (RFI)

- Resin film on top of the reinforcement
- Resin film heated and compressed



### Resin film infusion (RFI)

- Infusion of the resin under a flexible membrane
- Control of temperature and pressure



## Liquid composite modeling

The Vacuum Assisted Resin Infusion (VARI) process is a widely used method for manufacturing composite materials. It involves infusing resin into a dry fiber preform using vacuum pressure. This process is particularly advantageous for producing large, high-performance parts with complex geometries.

### 1. Preparation:

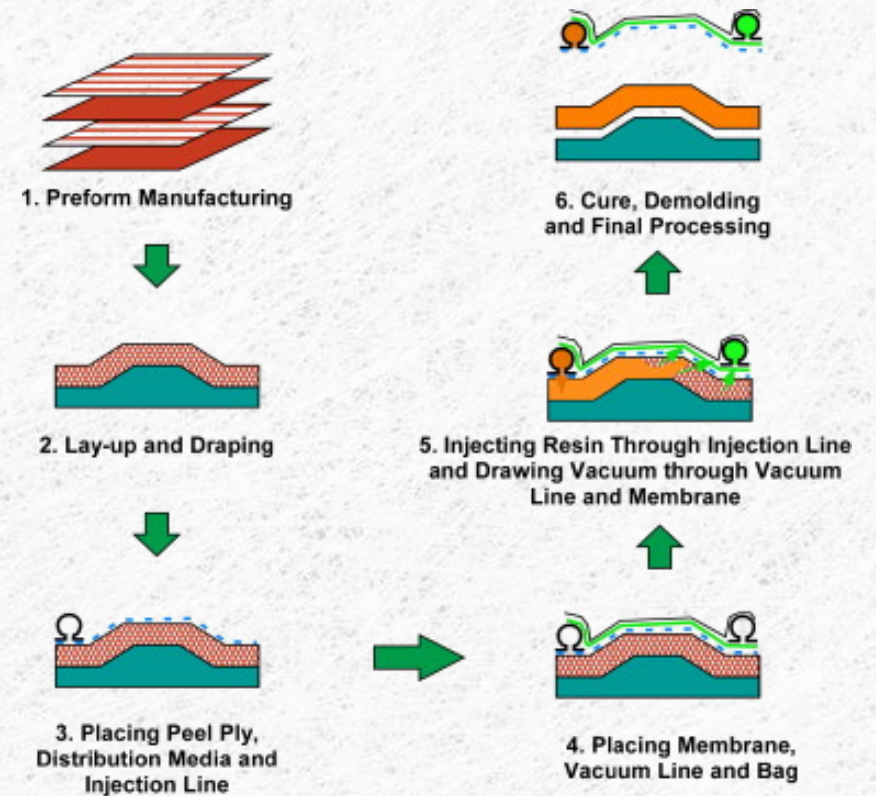
- The dry fiber preform is placed into a mold. The mold can be a single-sided tool with a flexible vacuum bag covering the top.

### 2. Sealing:

- The mold is sealed with a vacuum bag, ensuring that it is airtight. This step is crucial to maintain the vacuum pressure during the infusion process.

### 3. Vacuum Application:

- A vacuum pump is connected to the mold, creating a vacuum that removes air from the fiber preform, avoiding air pockets.



## Liquid composite modeling

The Vacuum Assisted Resin Infusion (VARI) process is a widely used method for manufacturing composite materials. It involves infusing resin into a dry fiber preform using vacuum pressure. This process is particularly advantageous for producing large, high-performance parts with complex geometries.

### 4. Resin Infusion:

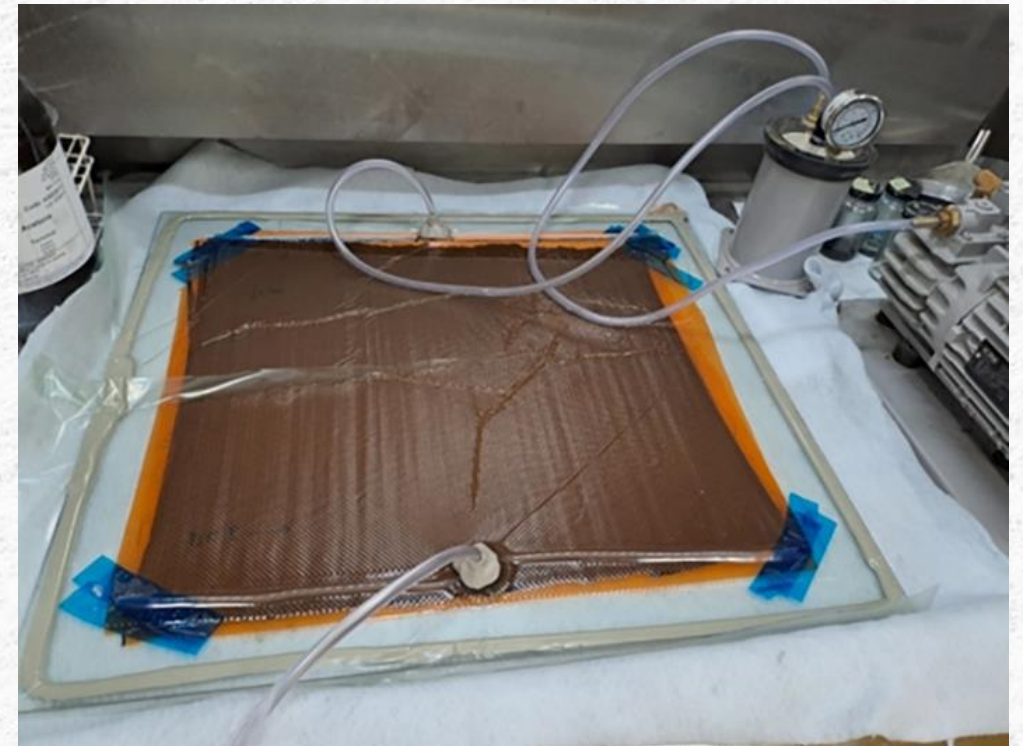
- Resin is introduced into the mold through strategically placed inlet ports. The vacuum pressure draws the resin into the fiber preform.

### 5. Curing:

- Once the resin has fully infused the fiber preform, the part is left to cure. This can be done at room temperature or with the application of heat, depending on the resin system used.

### 6. Demolding:

- After curing, the vacuum bag and mold are removed, and the finished composite part is taken out.



## Liquid composite modeling

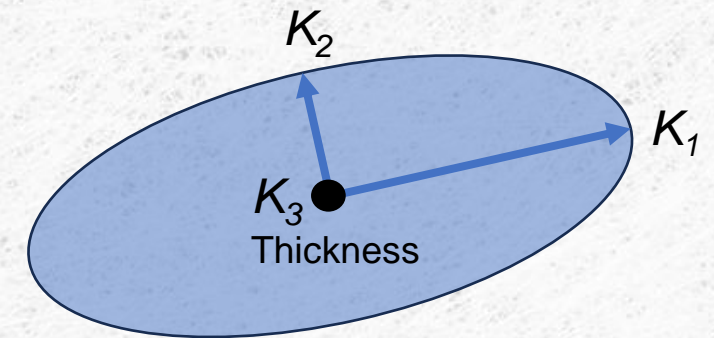
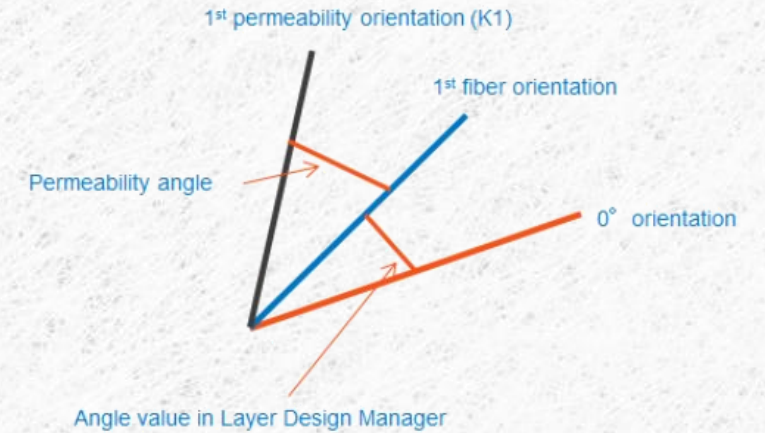
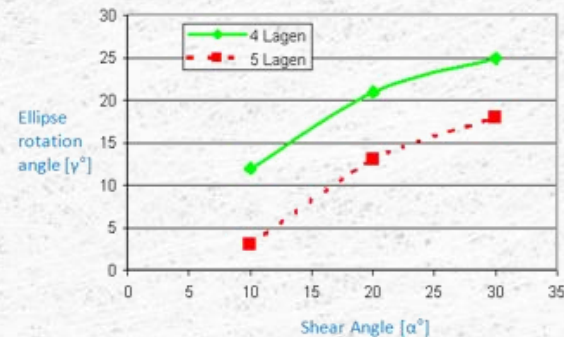
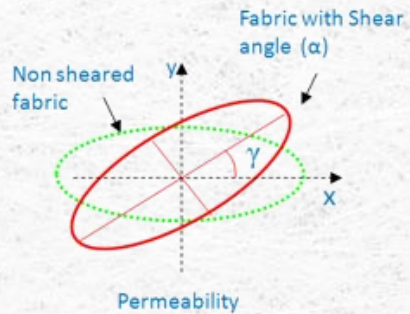
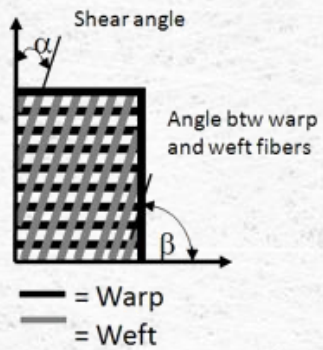
PARAMETER	SIMULATION INPUT	COMMENTS	POSSIBILITIES
Reinforcement	Permeability tensor (K1, K2, K3)	To be done for both fiber directions and also, for thickness direction in 3D models	Constant or Shear Angle and/or fiber content dependence
	Permeability angle	Angle between fiber direction and maximum permeability direction	Constant or Shear Angle and/or fiber content dependence
	Fiber Content	Only to know and control the resin volume	Constant or Shear Angle and/or initial fiber content dependence
Resin	Density	Only used for gravity cases	Constant
	Viscosity	For isothermal filling, only it is needed to know the viscosity value at the temperature of the resin during the process.	Constant or Castro-Macosko model or Lee model or temperature, time, and/or degree of cure dependence
	Capillary coefficient	Only to know and optimize the output void	Constant
	Optimal Capillary Number	Only to know and optimize the output void	Constant
	Micro-Macro void's function	Only to know and optimize the output void	Linear or logarithmic scale of void content vs capillary number

## Flow in porous medium

### Permeability

Maximum permeability value ( $K_1$ ), minimum permeability value ( $K_2$ ), transversal permeability ( $K_3$ ) and permeability angle must be measured.

The permeability is an intrinsic property of a lamina (reinforcement), and it can be dependent of the shear angle and the fiber content of the reinforcement. So, it is not dependent of the liquid (resin) used.



## Flow in porous medium

### Permeability measurement

The impregnation of the dry preform with liquid resin can be modeled as a flow through a porous medium, whose geometrical features are characterized by its permeability.

In-plane permeability is obtained by integrating Darcy's equation for one-directional flow under a constant pressure:

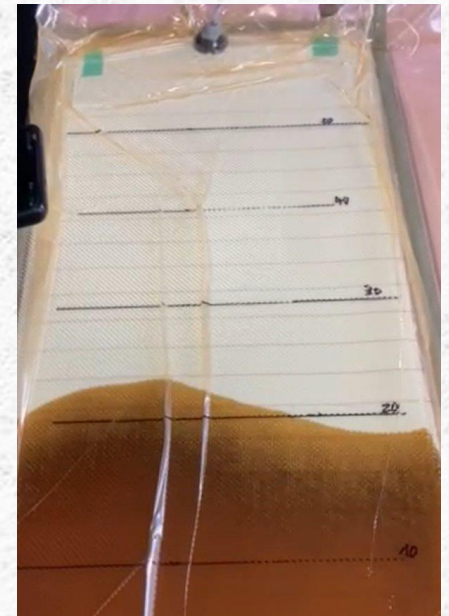
Where:

- $d(m)$  is the flow front
- $t$  is the time
- $\eta$  is the resin viscosity
- $V_f$  is the fiber volume fraction
- $\Delta p$  is the pressure difference

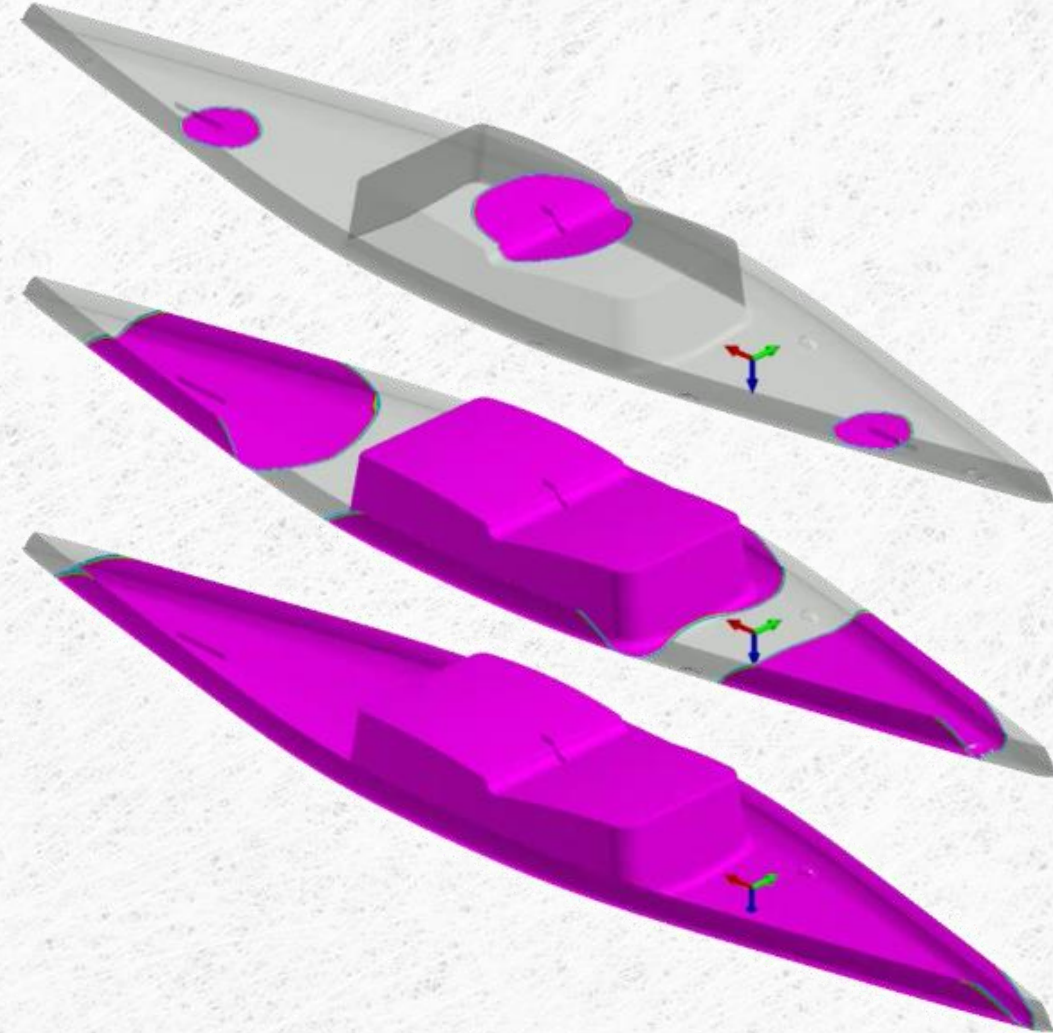
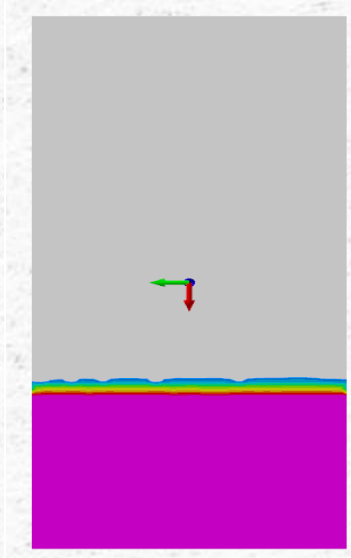
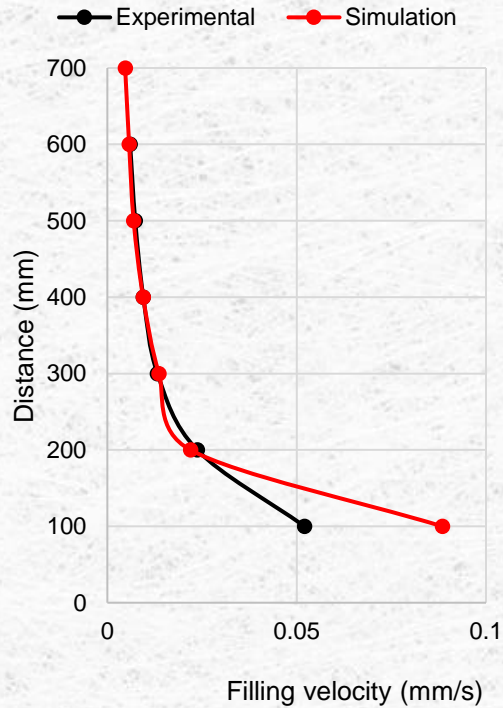
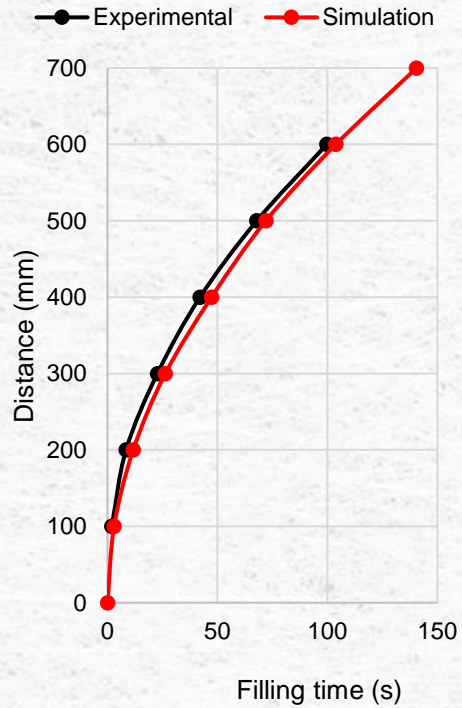
$$d(m)^2 = \frac{2K\Delta p}{\eta(1 - V_f)} t$$

By extrapolating the slope of the linear fitting of the experimental data, it is possible to calculate the permeability  $K$  along the flow direction:

$$K = \frac{\text{Slope} \cdot \eta(1 - V_f)}{2\Delta p}$$



## Flow in porous medium - MC4 Specific Application



# Contact and acknowledgements



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### Website

<https://www.mc4-project.eu>



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The partners of MC4 are:

- Profactor** (Austria, coordinator)
- FIDAMC** (Spain)
- GAIKER** (Spain)
- CIDETEC** (Spain)
- STFI** (Germany)
- 3B Fibreglass** (Belgium)
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- CEA** (France)
- Techtera** (France)
- Amura** (Spain)
- Managing Composites** (Spain)
- IRES** (Greece)
- LAB23** (Italy)
- Chomarats** (France)
- i-RED** (Austria)



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**Thank you for your attention**



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# ANNEX C



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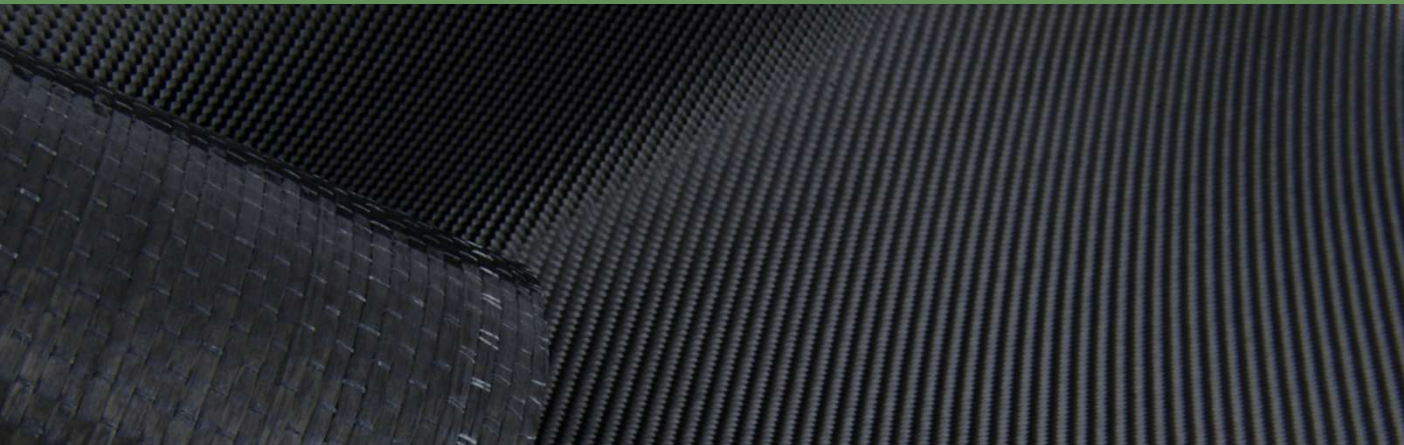
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# **EDUCATIONAL MATERIAL FOR CIRCULARITY: USING RECYCLED GFRC IN PRODUCT DESIGN**

VENICE, 05/02/2025



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## Summary

The Educational material consists of the following sections:

- THE MC4 project background
- Scope and Timeframe
- Purpose and Objectives
- The MC4 project's partnership
- The urban furniture concept
- Key message
- The Soul bench - Circular Process



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## The MC4 project background

**The MC4 project - Multi-level Circular Process Chain for Carbon and Glass Fibre Composites**, is a European partnership aiming to establish circular approaches for carbon and glass fibre composites.

After a 3 years implementation, MC4 make the European carbon and glass fibre value chains more circular, independent and competitive.

LAB23 is an urban furniture manufacturer involved in MC4 as industrial partner to develop a new product focusing on recycling and circularity of Glass Fibre composites.





## Scope and Timeframe

- Establish a multi-level circular process for glass fibre composites, with processes developed for short-term impact on the urban furniture industry.
- Develop efficient and economically realistic processes adapted to the specific value chain.
- To provide the European industry with the means to master and own its manufacturing processes for recycled composites.
- Timeframe: 36 months, MC4 started in April 2022 and the end of the project is March 2025.





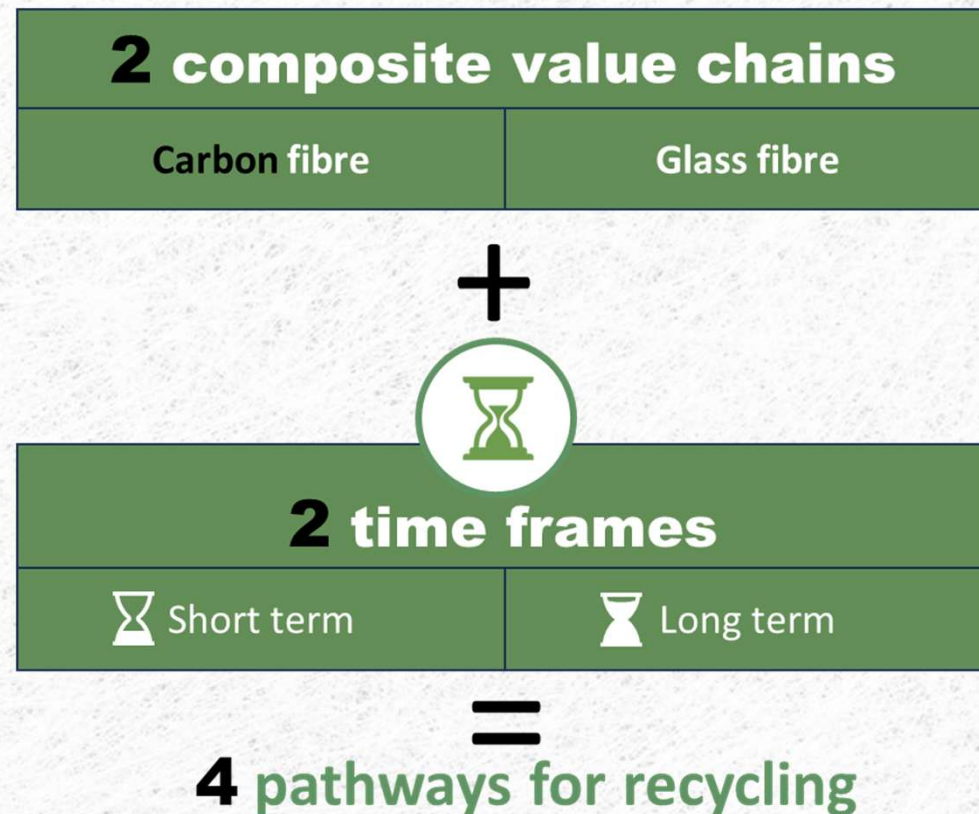
## Purpose and Objectives

The SOUL BENCH is one of the products validating a circular process chain for glass fibre composites.

Why is it happening & expected results:

The MC4 Glass Fibre short term activities are based on the development of different value chains, including a hand lay-up and casting of a shredded GFRC urban bench.

Building a product demonstrator in urban furniture will highlight the advantages and disadvantages compared to the standard non-recyclable product.





# The MC4 project's partnership

- Profactor (Austria) – The Project Leader
- FIDAMC (Spain)
- GAIKER (Spain)
- CIDETEC (Spain)
- STFI (Germany)
- 3B Fibreglass (Belgium)
- VDL Fibertech Industries (the Netherlands)
- CEA (France)
- Techtera (France)
- Amura (Spain)
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- i-RED (Austria)
- NOMA RESINS (Poland)



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## The MC4 project's partnership

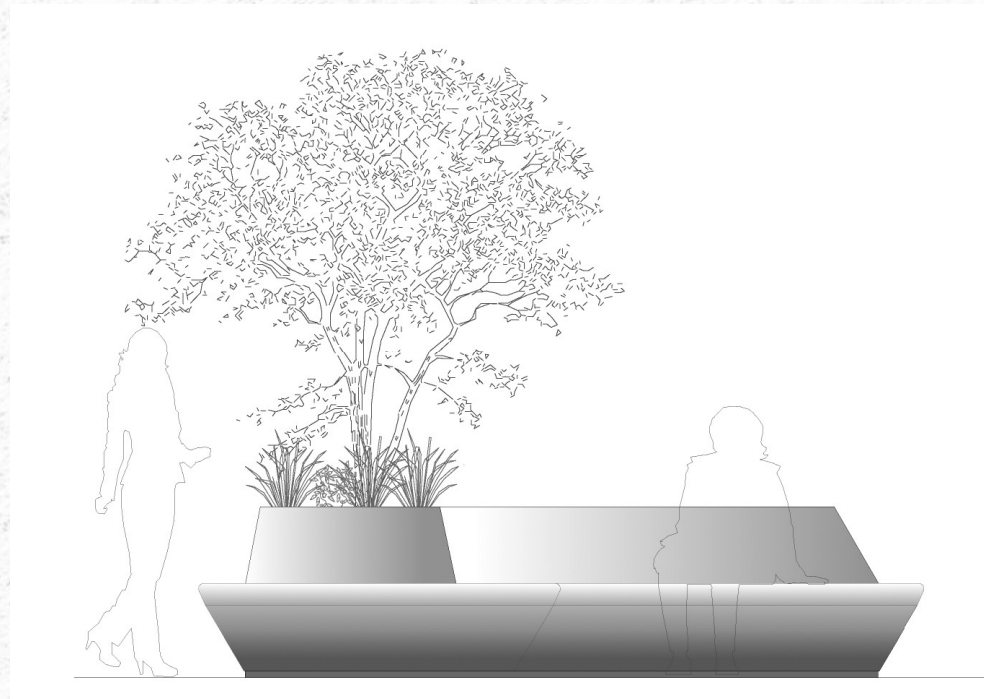
The MC4 partners involved in the Glass Fibre short-term value chain, specifically support LAB23 from waste collection to manufacturing and design, serve as a testament to the power of joined-up thinking and action in achieving a truly sustainable outcome.

The circular process chain within MC4 starts with the collection of waste in the Netherlands by VDL and its shipment to LAB23 in Italy, while future plans include a local supply chain of the same End-of-Life composite material from authorised centres for the recycling of composite waste.



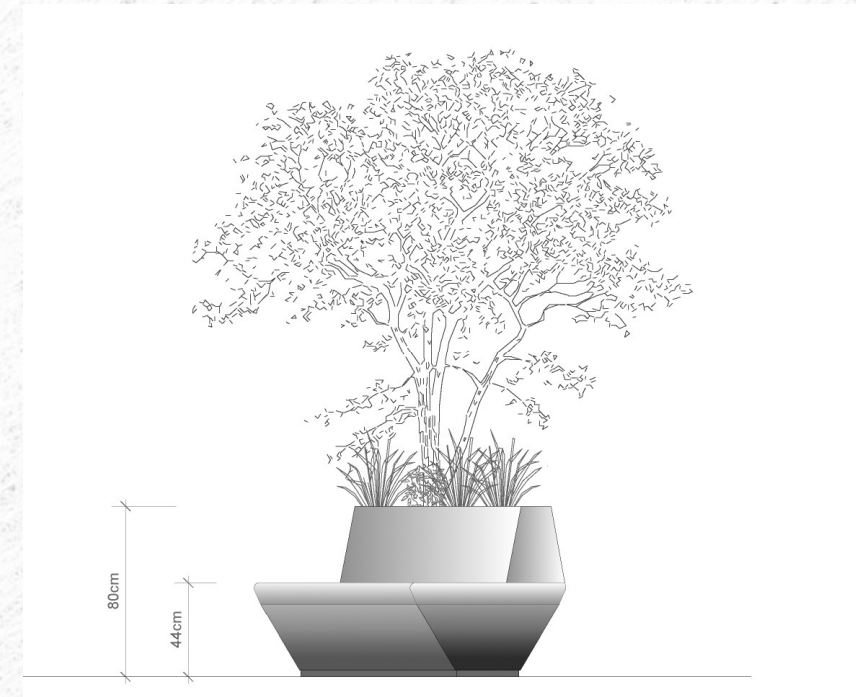
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The LAB23 urban furniture concept is based on the use of shredded composites, a mixture of glass fibre and resin, which offer many advantages in terms of strength, durability and environmental impact. However, the production of large, organic shapes is a significant challenge due to the nature of the recycled composite material. In MC4, the main challenges in producing a prototype bench in recycled glass fibre composite and the solutions used to overcome them were identified.



The new urban furniture concept has involved various challenges, especially in processing large, organic shapes.

- **Creating Organic Shapes:** One of the main goals in modern urban furniture production is the creation of organic, fluid, and complex shapes. However, recycled composite material tends to be less malleable than virgin materials, making it difficult to create curves and intricate details.
- **Managing Waste:** During the production of composite material urban furniture, residues and scraps are generated, which can be challenging to manage. The scraps can be reused in production process if properly treated.





## The Urban Furniture Concept

To achieve objects with organic shapes, the recycled composite material provided by VDL underwent further grinding. This was a fundamental step to improve the workability and quality of the provided composite material. This process allowed for obtaining a finer and more homogeneous granulometry, facilitating the processing and creation of more complex shapes.

The further grinding also contributed to reducing the wear on the working tools, making the process more efficient and less costly.





## The Urban Furniture Concept

LAB23 implemented recycling of production scraps: The composite material waste generated during the manufacturing process of the urban furniture is further ground and reintegrated into the production of a new product.

In this way, the amount of waste is reduced, and the use of the material is maximized, contributing to a more sustainable urban furniture production cycle, closing the loop with a relevant improved circularity of secondary raw material.



To achieve objects with organic shapes, the recycled composite material provided by VDL underwent further grinding. This was a fundamental step to improve the workability and quality of the provided composite material. This process allowed for obtaining a finer and more homogeneous granulometry, facilitating the processing and creation of more complex shapes. The further grinding also contributed to reducing the wear on the working tools, making the process more efficient and less costly.





## The Urban Furniture Concept

Following successful testing of a fine grinding process applied to recycled glass fibre waste, LAB23 proceeded with the production of the SOUL bench prototype. LAB23 successfully demonstrated that this recycled composite material can be used to create a robust and durable urban furnishing with flowing organic shapes, while adhering to strict sustainability principles.

The SOUL bench represents a significant step in our pursuit of urban furniture solutions that combine innovative design with a fully circular approach, ensuring the material can be fully recycled at the end of the product's life.





## Key message

- The SOUL bench, designed by LAB23 for the MC4 project, is manufactured using a glass fibre mould and contains 50% recycled glass fibre composite (GFRC) and is 100% recyclable.
- With this innovative circular process, the SOUL bench embodies sustainability, durability and refined design, making it an outstanding piece of urban furniture.



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## The Soul bench – The full Circular Process

- This presentation of the Soul Bench full Circular Process will cover shredding, processing, composite preparation, moulding, finishing, installation and finally reprocessing at the end of life.
- Emphasis is placed on the specific techniques used for the Soul bench, such as hand lay-up and casting, with detailed explanations of resin preparation, including mixing ratios and curing processes.



## Step 1: Waste Collection

- **Sourcing:** in MC4 project, We've established a partnership with VDL, his customer, who is supplying end-of-life GFRC automotive parts (specifically from buses).
- **Collection:** We're setting up a GFRC waste collection system for future scale-up, targeting local recycling centres, manufacturers, and demolition companies as key waste sources.



*Images: Automotive parts – bus side skirt*

## Step 2: Shredding & Processing

- **Shredding/Grinding:** We use an industrial granulator to reduce the GFRC waste into smaller pieces (flakes/strands) suitable for the "Soul bench".
- Effective dust control is essential during this stage.
- **Cleaning (Optional):** If necessary, the shredded GFRC will be cleaned via air blasting to remove any remaining contaminants or loose fibres.



*Image: Shredded GFRC granules*

## Step 3: Composite Preparation

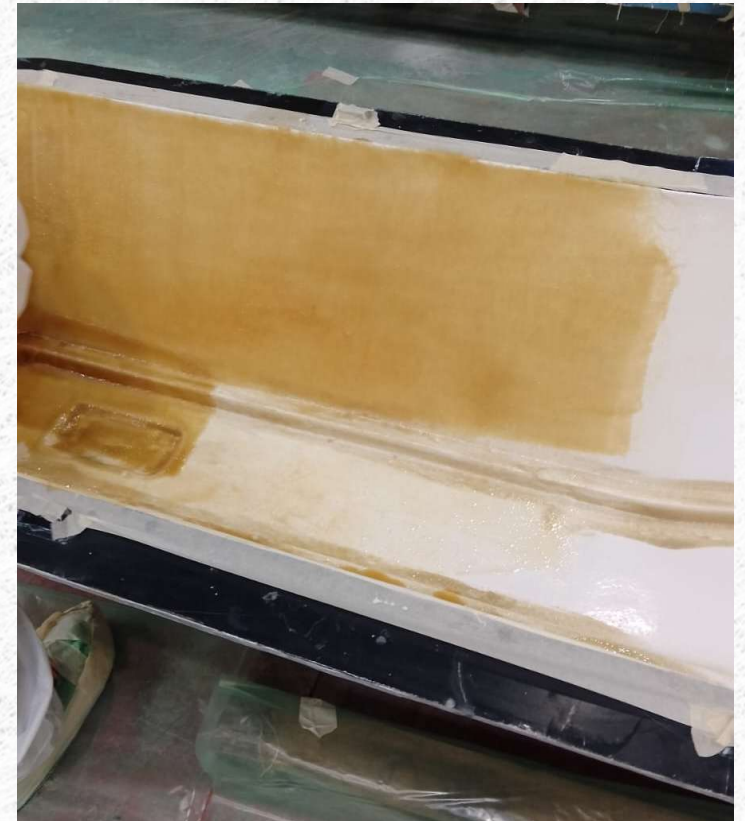
- **Polyester Resin Preparation:** Unsaturated polyester resin is prepared according to the manufacturing manager's instructions, using 55kg per bench.
- **Mixing:** 100kg of shredded GFRC is thoroughly mixed with the prepared resin, ensuring even fibre distribution throughout the resin matrix. The fibre-to-resin ratio will be carefully controlled to achieve the desired strength and properties in the final product. A mechanical mixer is used. We also add fillers (e.g., recycled glass powder) to extend the material and enhance specific properties.



*Image: GFRC in Polyester resin*

## Step 4: Mould Preparation

- Mould Design & Fabrication: The urban bench mould is designed and fabricated from Glass fibre as suitable material. The design will consider demoulding and the desired surface finish.
- Before production begins, a release wax is applied to the mould. This crucial step ensures easy removal of the finished product from the mould.



*Image: Application of release wax*

## Step 5: Gelcoat Application

- The first visible layer applied is the gelcoat, which defines the external surface finish. This is manually applied using a roller to ensure uniform coverage.



*Image: Gelcoat application*

## Step 6: Glass fibre Layering

- Once the gelcoat has set, Glass fibre matting is layered inside the mould. Different weights of Glass fibre are used depending on the structural requirements of specific areas.



*Image: Fiberglass layering*

## Step 7: Application of the GFRC Mixture

- Lay-up/Casting: Hand Lay-Up:** For hand lay-up, a gelcoat resin layer is applied to the mould, followed by 25kg of virgin glass fibre, ensuring homogenous distribution. The shredded GFRC mixture is then applied, again ensuring even distribution and consolidation. These layers are repeated until the desired thickness is achieved.
- Casting:** For casting, the mixture is poured into the mould, taking care to ensure complete filling and minimise air bubbles.



*Image: Application of GFRC mixture*

## Step 8: Mould Closure and Curing

- After the layup and casting, the mould is closed and sealed. The curing process begins, allowing the material to harden.
- **Curing:** The composite is cured according to the resin manufacturer's recommendations, with careful control of temperature and humidity for optimal results.
- Once fully cured, the bench is carefully removed from the mould.



*Image: Mold closure and curing*

## Step 9: Demoulding and Finishing

- **Demoulding:** Carefully remove the cured GFRC bench from the mould.
- **Finishing:** Perform any necessary finishing operations, such as trimming or polishing, to achieve the desired surface finish and dimensions.
- This final step involves bodywork refinements, ensuring a smooth and polished surface. This stage determines the aesthetic quality and durability of the Soul bench.



*Image: Final surface finishing*



## Useful links - Contact



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### Website

<https://www.lab23.it/>



### LinkedIn

<https://www.linkedin.com/company/mc4-project>



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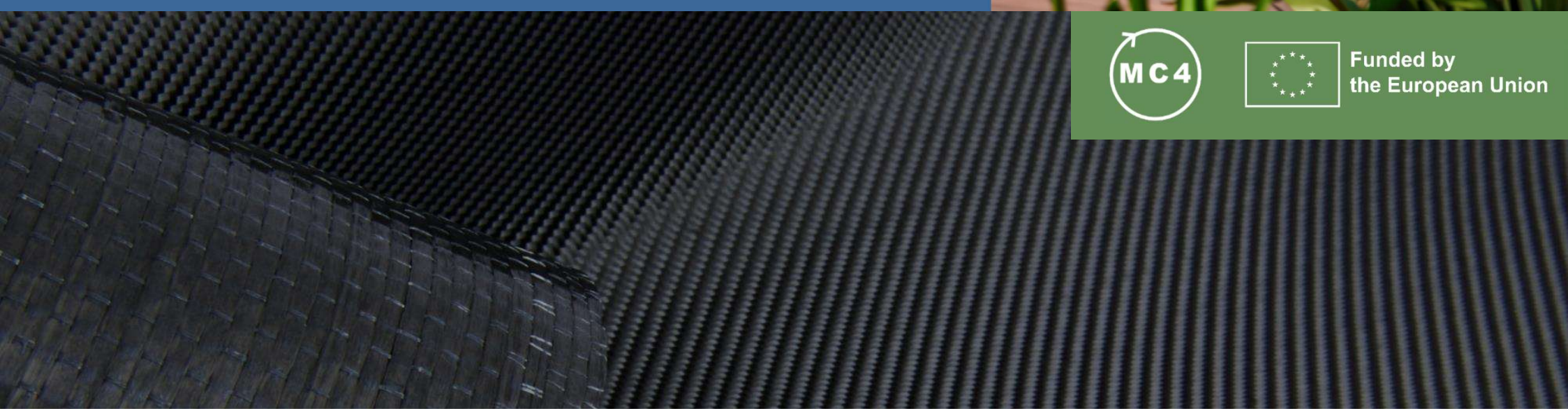




**For further information visit [www.lab23.it](http://www.lab23.it)**

**Please don't hesitate to contact the Technical Department [tecnico@lab23.it](mailto:tecnico@lab23.it) to ask direct questions about the processes involved and to request additional materials.**

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