LCA of CFRP in Aerospace: Energy Modelling of Autoclave Curing

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Outline

- Motivation and objectives
- Autoclave curing
- Energy monitoring using power meter
- Parametric models for energy consumption
- Results and discussion
- Conclusion

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CFRP in Aerospace Applications - Advantages

High Stiffness (Rigidity)	High specific strength	High Corrosion and Fatigue Resistance

Production of Lightweight Structures

Increased Fuel Efficiency

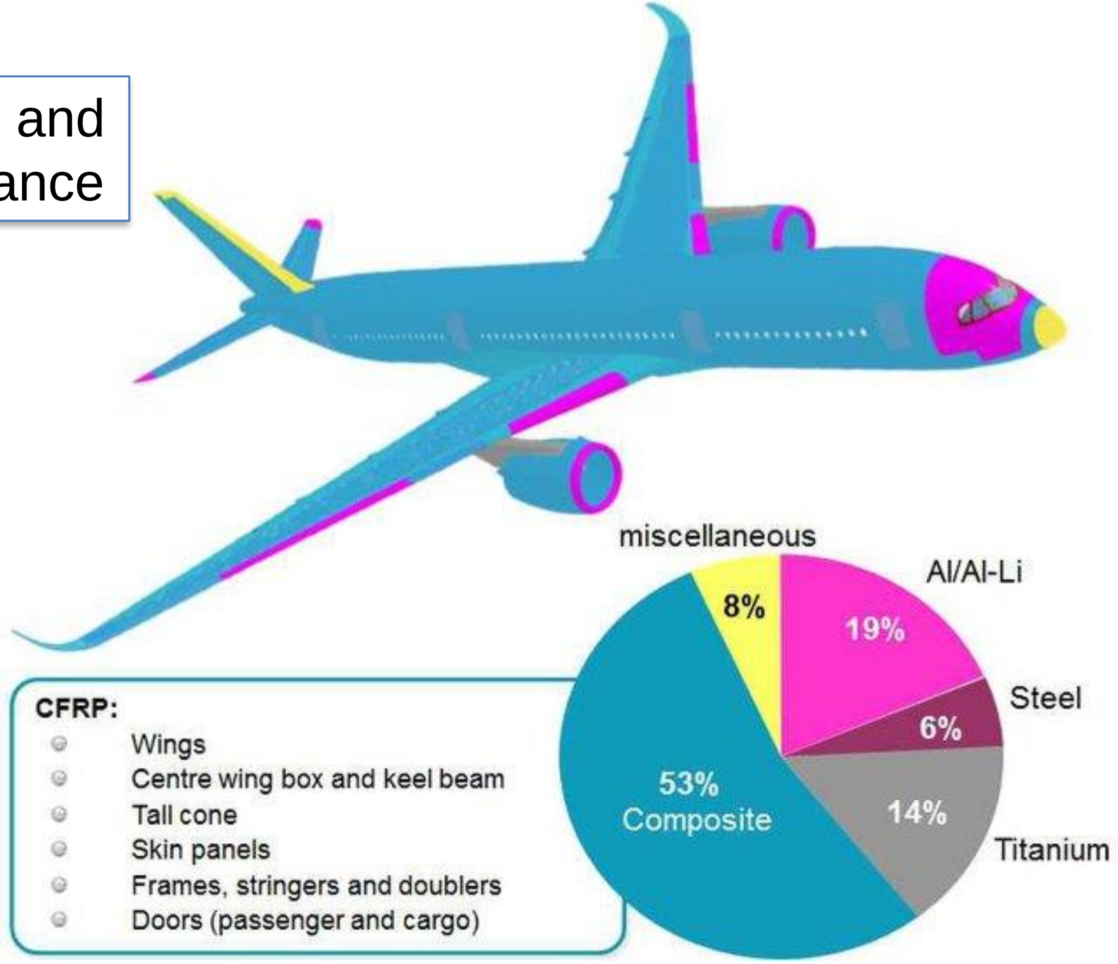
25% in Boeing 787 (ICCT 2017)

Lower Operating Cost

Up to 3.5% (NASA)

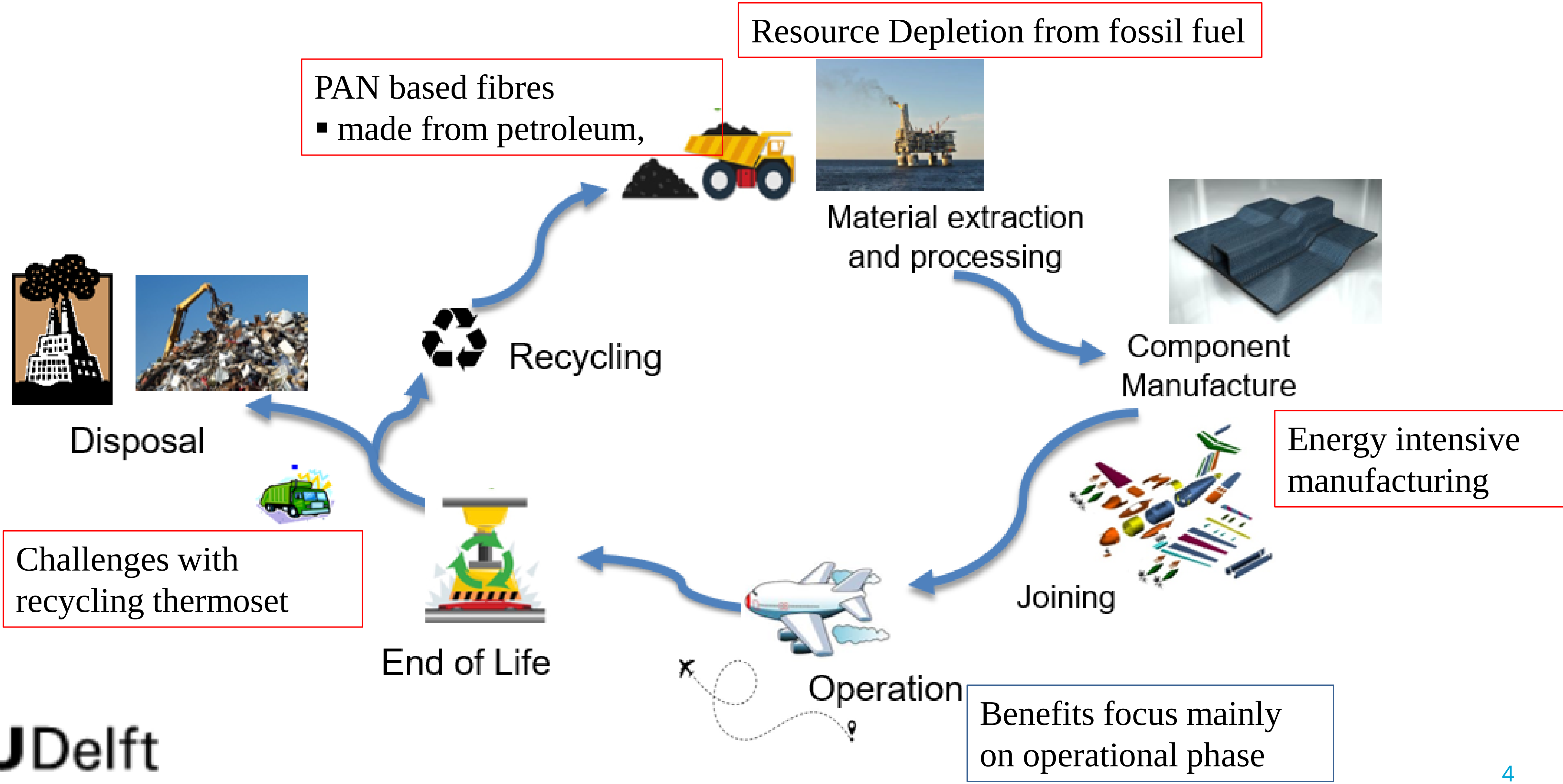
Reduced Emissions

Up to 20% of aviation CO_2 target



Materials used in Airbus A350 XWB (Airbus Operations)

CFRP Value Chain in Aerospace Applications



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Manufacturing CFRP in Aerospace Applications

➢ Mainstream is thermoset CFRP with autoclave curing

Process Flow: Storage → Cutting → Tool preparation → Layup and Debulking → Autoclave Curing → **CF/Epoxy panel**

Manual Collation

Automated Collation – AFP Robots

- What are the energy Intensive process Steps?
- What parameters influence them?

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Goal and Objectives

- Create reliable energy inventory data for autoclave CFRP manufacturing
  - Can be used in LCA studies and cost estimations
- Identify hot spots regarding energy consumption
- Identify process and design parameters that influence energy consumption
  - For optimisation

How?

- Energy monitoring using power meter – Experimental study
- Energy estimation using thermodynamics based models

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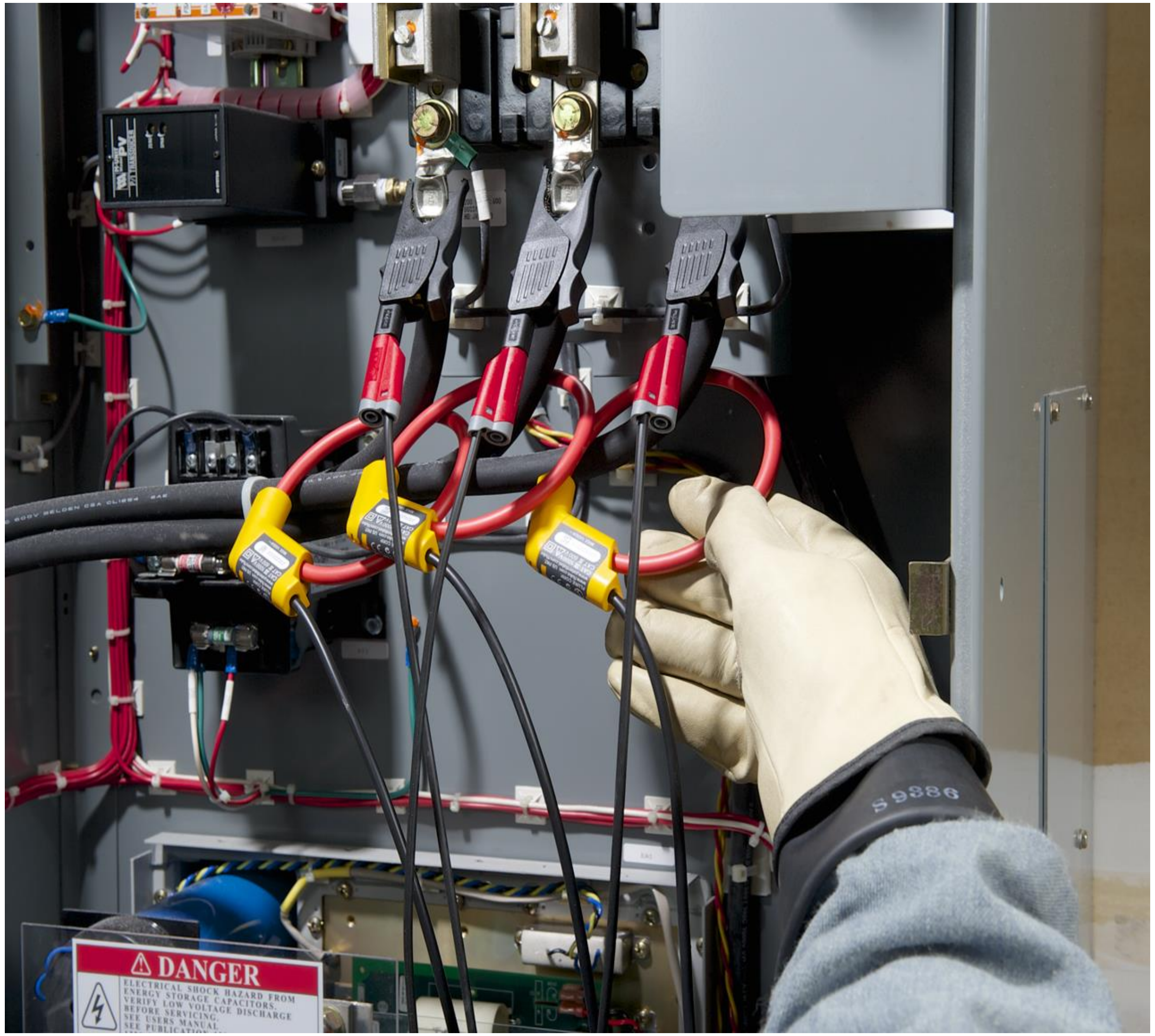
Energy Monitoring: CFRP Panel Manufacture

- ✓ Manufacture a CF/Epoxy panel via manual collation and autoclave curing.
  - Monitor Energy Consumption
    - Using 3-phase Power meter
    - Convert power logs to energy logs - integral
- ✓ Identify process steps with the most energy consumption



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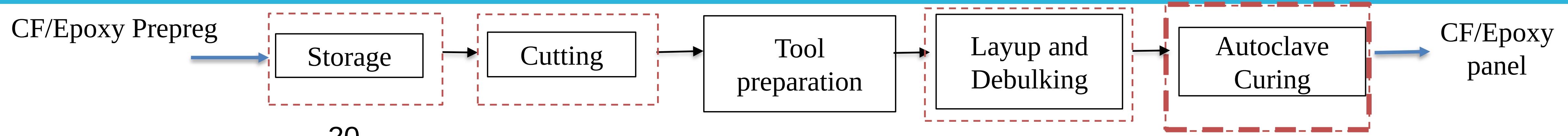
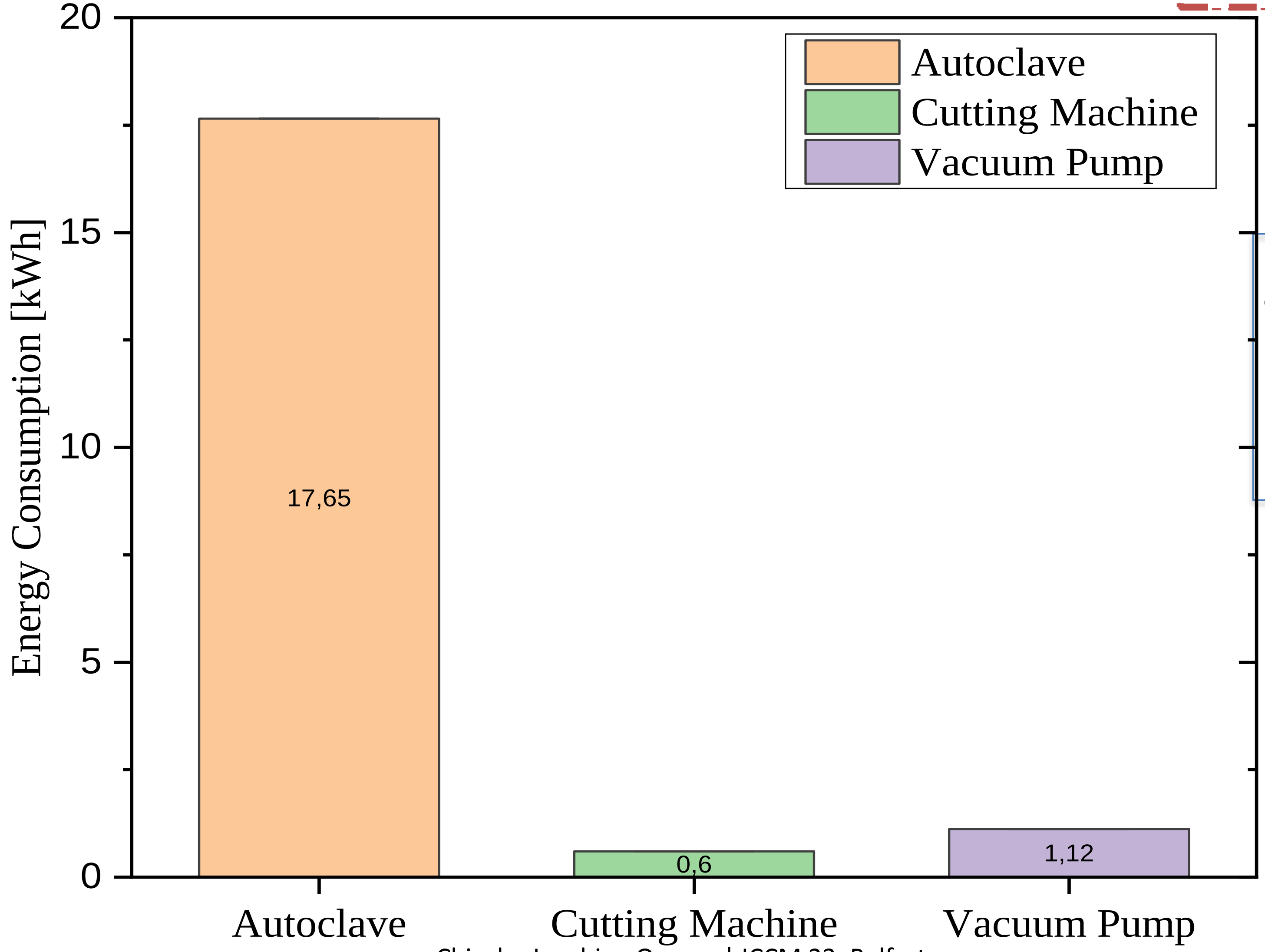
Results: Energy Monitoring

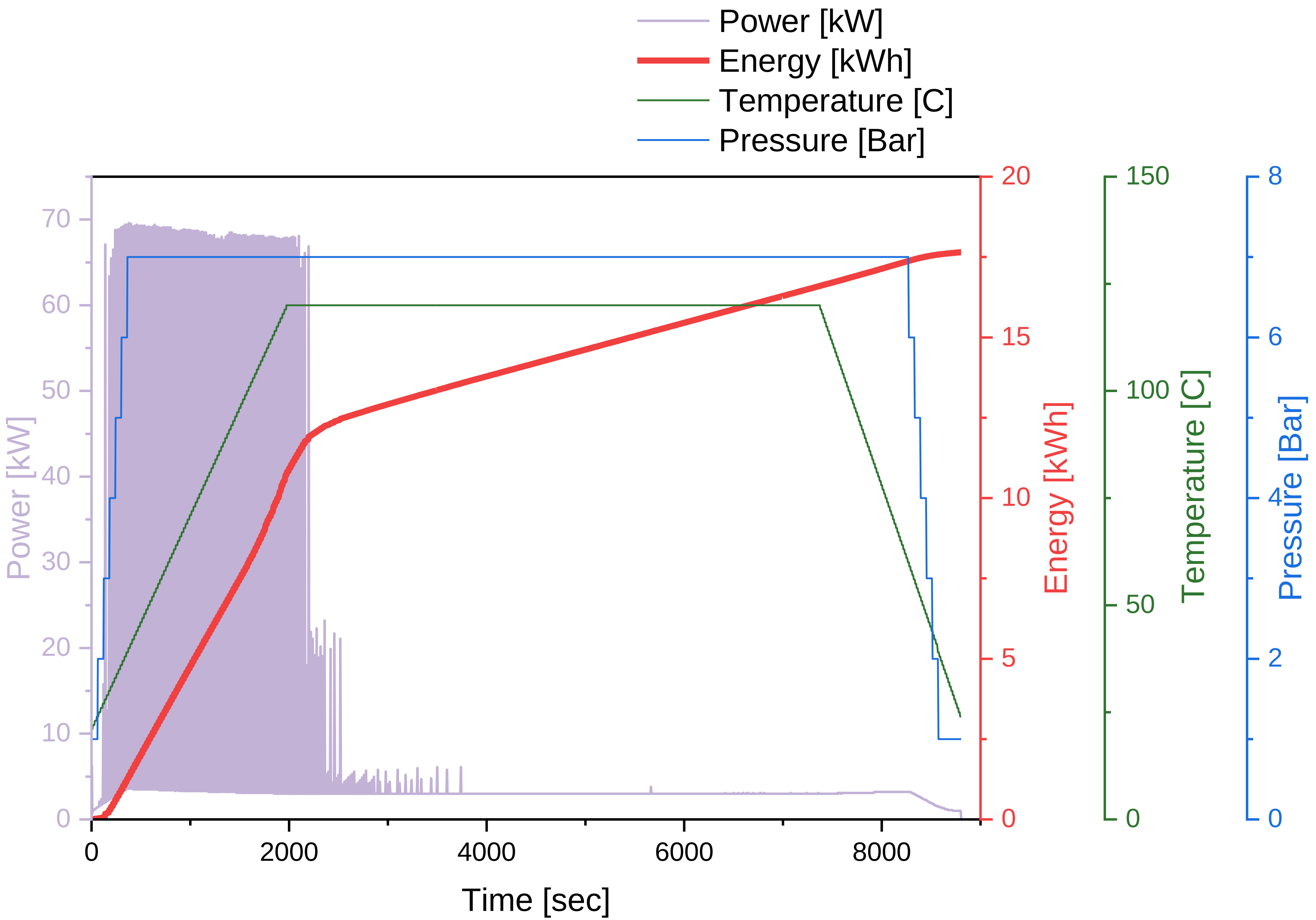




- Autoclave contributes 91%

Results: Autoclave Energy Monitoring

- Power Log
- Energy Log 17.6kWh
- First 35 mins stood out
- Temperature and Pressure Cycle



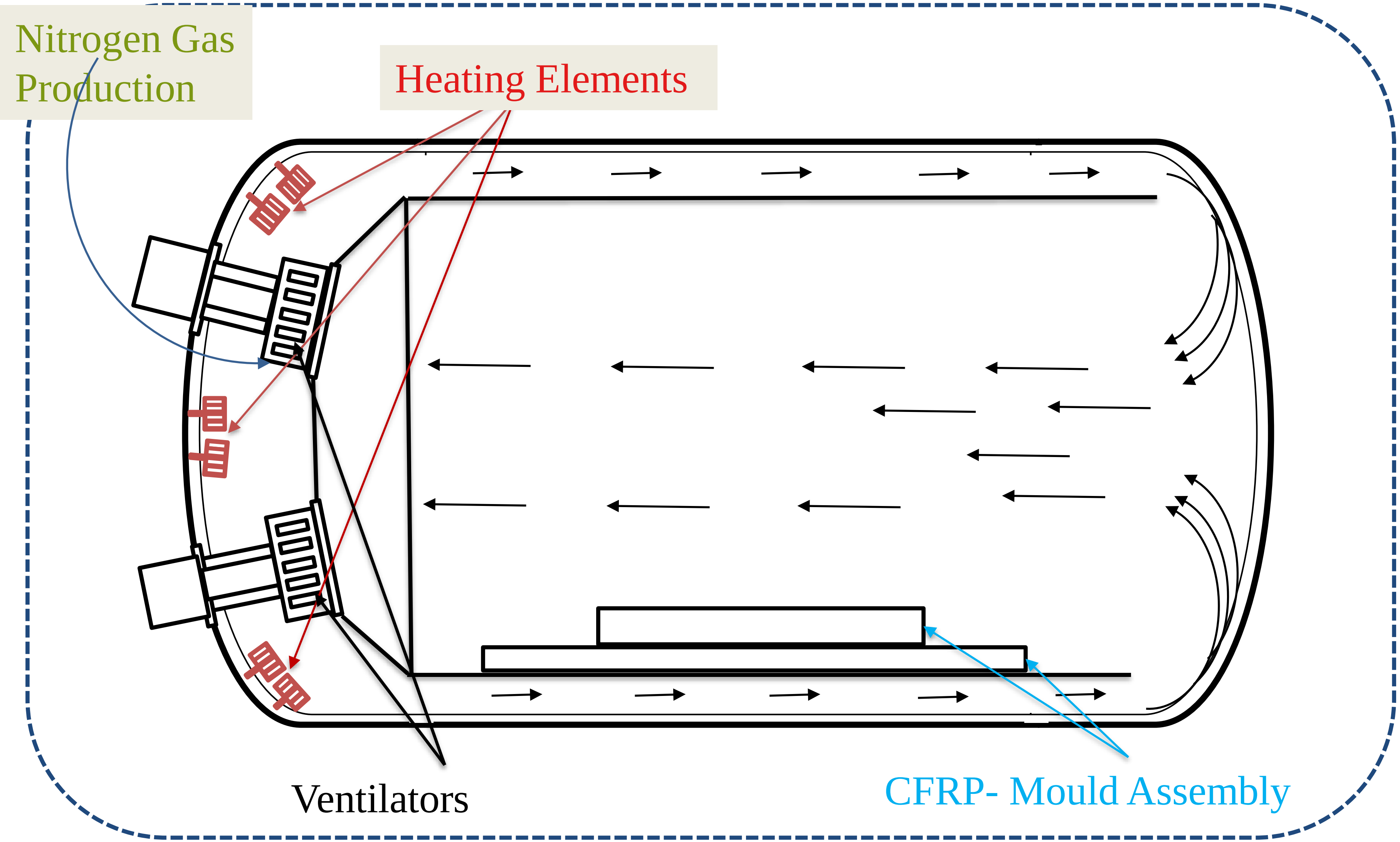
Thermodynamics Based Models

Two different models were used

- MRT LBM – Multirelaxation Time Lattice Boltzman Method
- Analytical Method

Why?

- Parametric and Scalable
- Breakdown energy consumption - Heat absorbing elements and heat losses

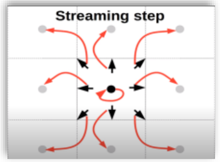


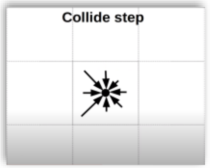
Control Systems

Thermodynamics Based Models: MRT LBM Method

2D Multi-Relaxation Time (MRT) lattice Boltzmann method

$$\underbrace{f_i\left(x+\vec{e}_i\partial t, t+\partial t\right) = f_i\left(x,t\right)}_{\text{Streaming}} - \underbrace{\frac{1}{\tau}\left(f_i\left(x,t\right) - f_i^{eq}\left(x,t\right)\right)}_{\text{Collision}}$$





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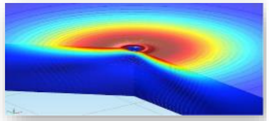
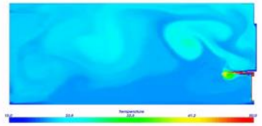
Energy Equation - Navier-Stokes Method

$$\frac{\partial T}{\partial t} = \boxed{\frac{k}{\rho C_p}\nabla^2 T} - \boxed{\vec{u}\cdot\nabla T}$$

Diffusion term: Nonlinear advection term





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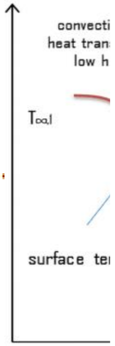
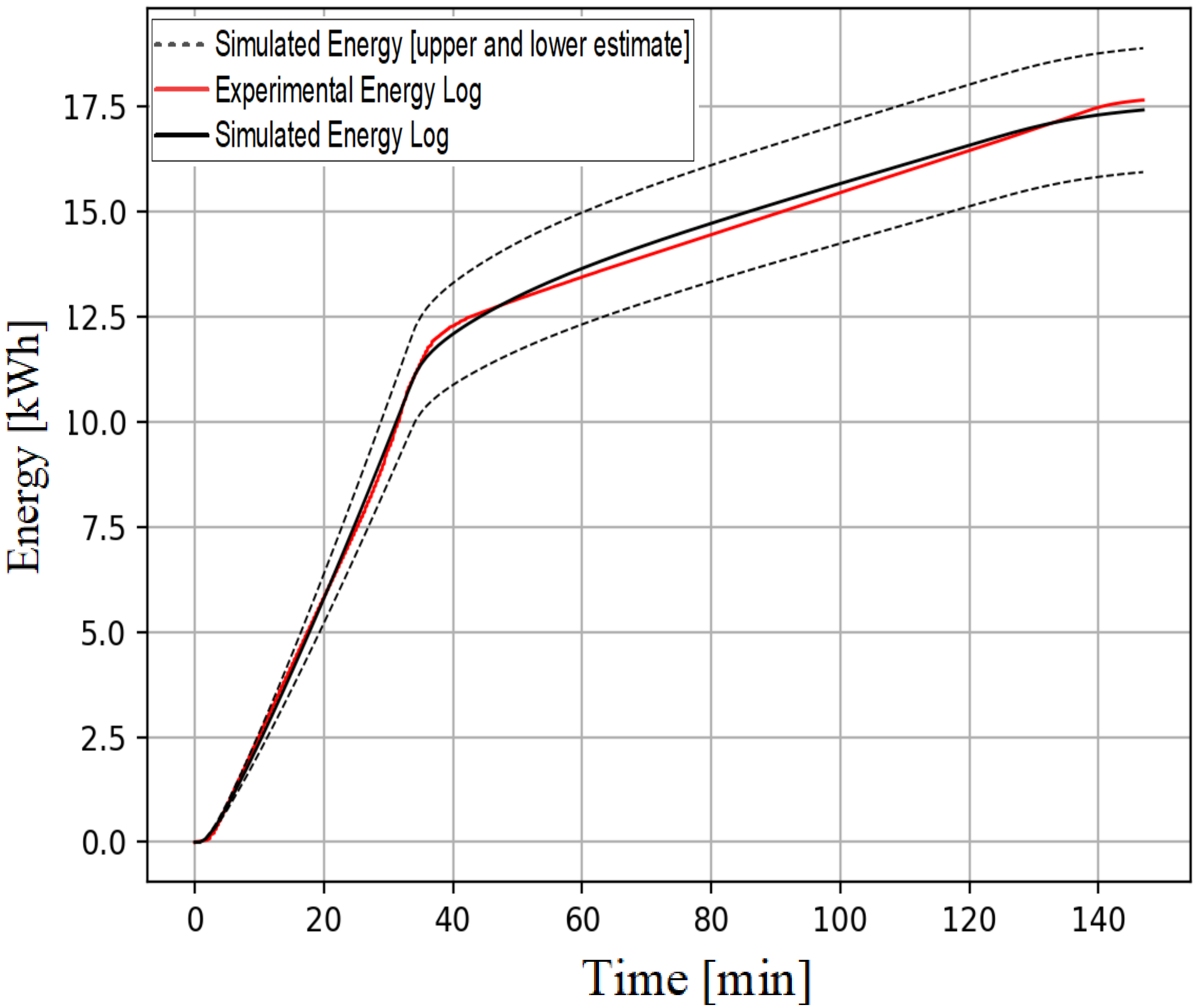
Fourier Heat Equation in 2D with convective boundary conditions

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right)$$



Simulated Autoclave Energy Consumption



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Thermodynamics Based Models: Energy Conservation

Ist Order Thermodynamics Law: Energy Conservation

$$Q_{inflow} = \frac{Q_{heat} + Q_{loss}}{\eta_{eff}} \times \eta_{Loading}$$

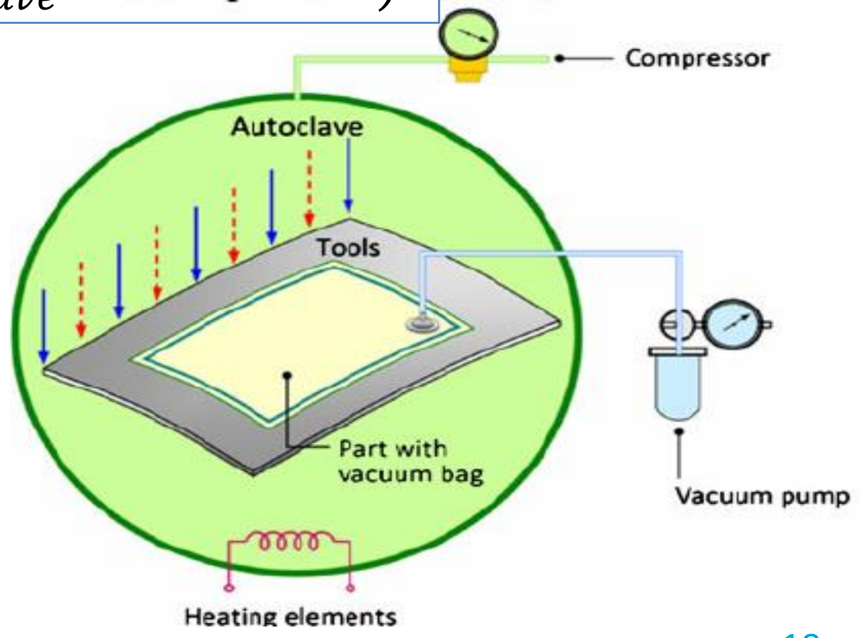
$$Q_{heat} = \rho . V . C_p \frac{\partial T}{\partial t}$$

$$Q_{heat} = \left(M_F C_{p_F} + M_R C_{p_R} + M_{con} C_{p_{con}} + M_{air} C_{p_{air}} + M_{autoclave} C_{p_{autoclave}}\right) . \left(T_{cure} - T_\infty\right)$$

$$Q_{loss} = A \times \frac{K_a}{s} \times (T_r - T_{out}) \times t$$

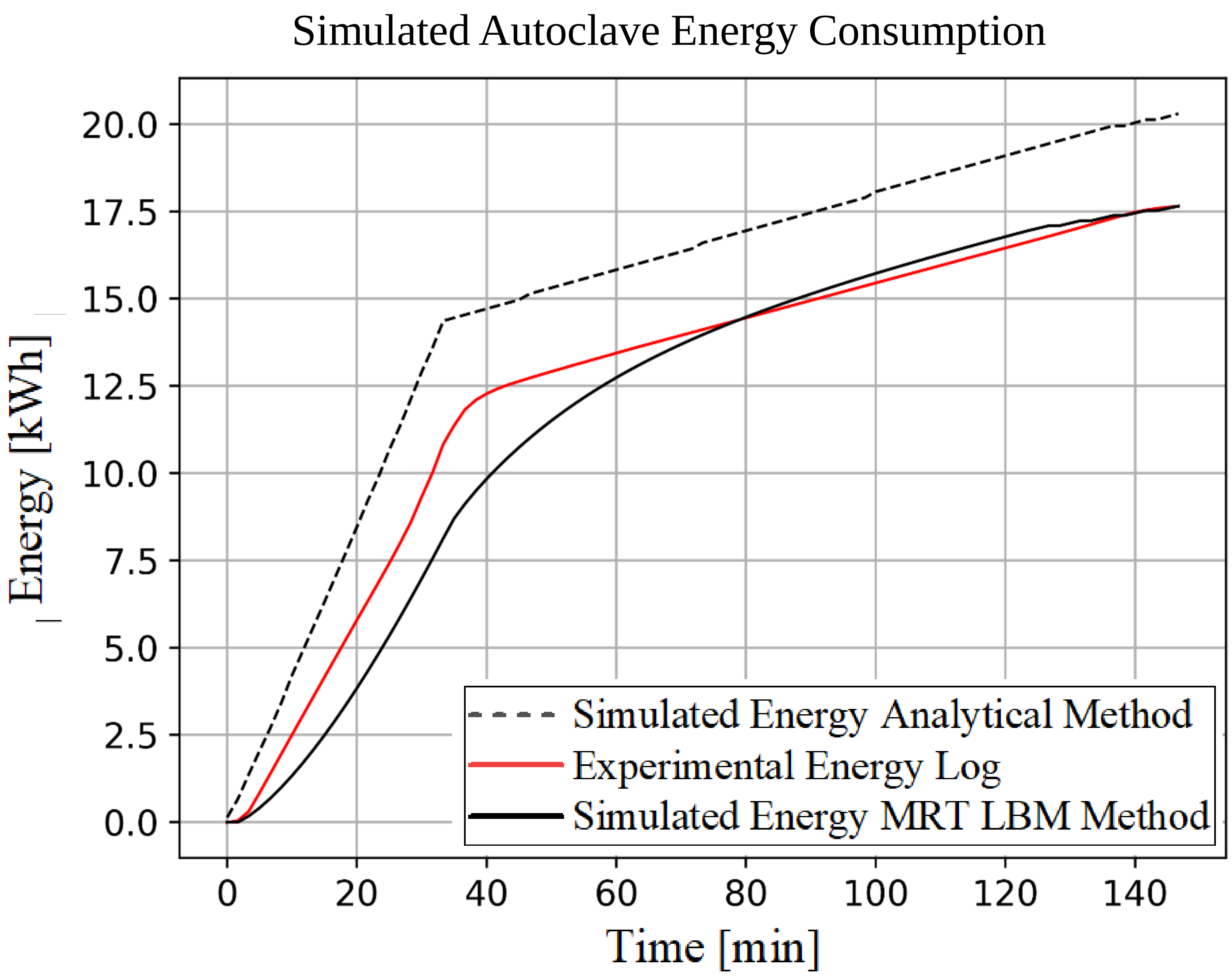
Considering heating energy for heating up only laminates,

$$Q_{heat_L} = \rho . V . C_p \frac{\partial T}{\partial t} = h . A (T - T_\infty)$$



Results: Model Comparison

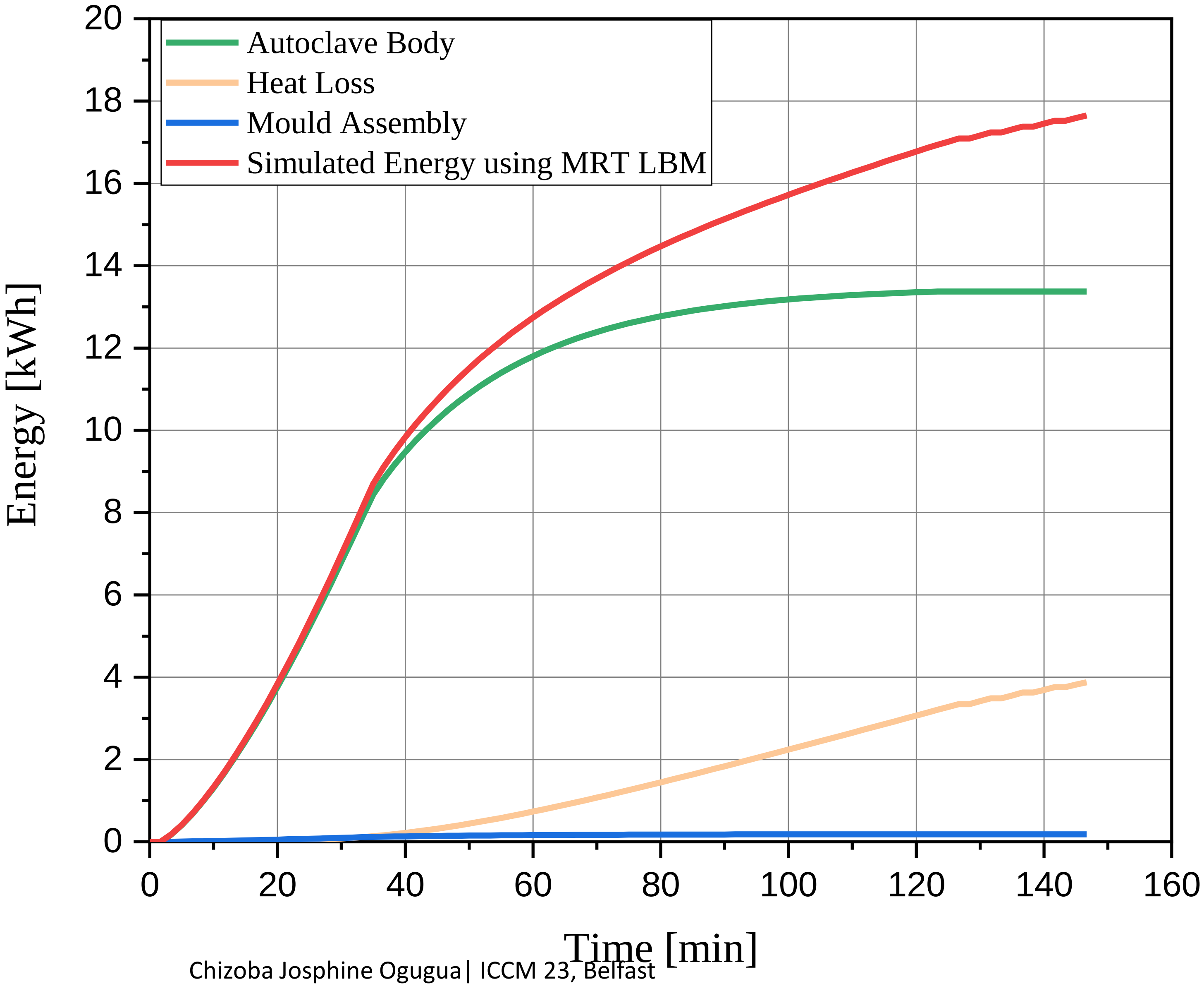
- ✓ 10% difference between the two methods
- ✓ MRT LBM was a better match to the monitored result (only 1% difference.)
- ✓ Analytical Method has the least computational effort



Results: Energy Breakdown

Energy consumed by each heat absorbing element within the autoclave.

- ✓ Heat absorbed by the composite part < 3%
- ✓ Heat transfer to autoclave body contributed 75%
- ✓ Heat loss through the walls 22%



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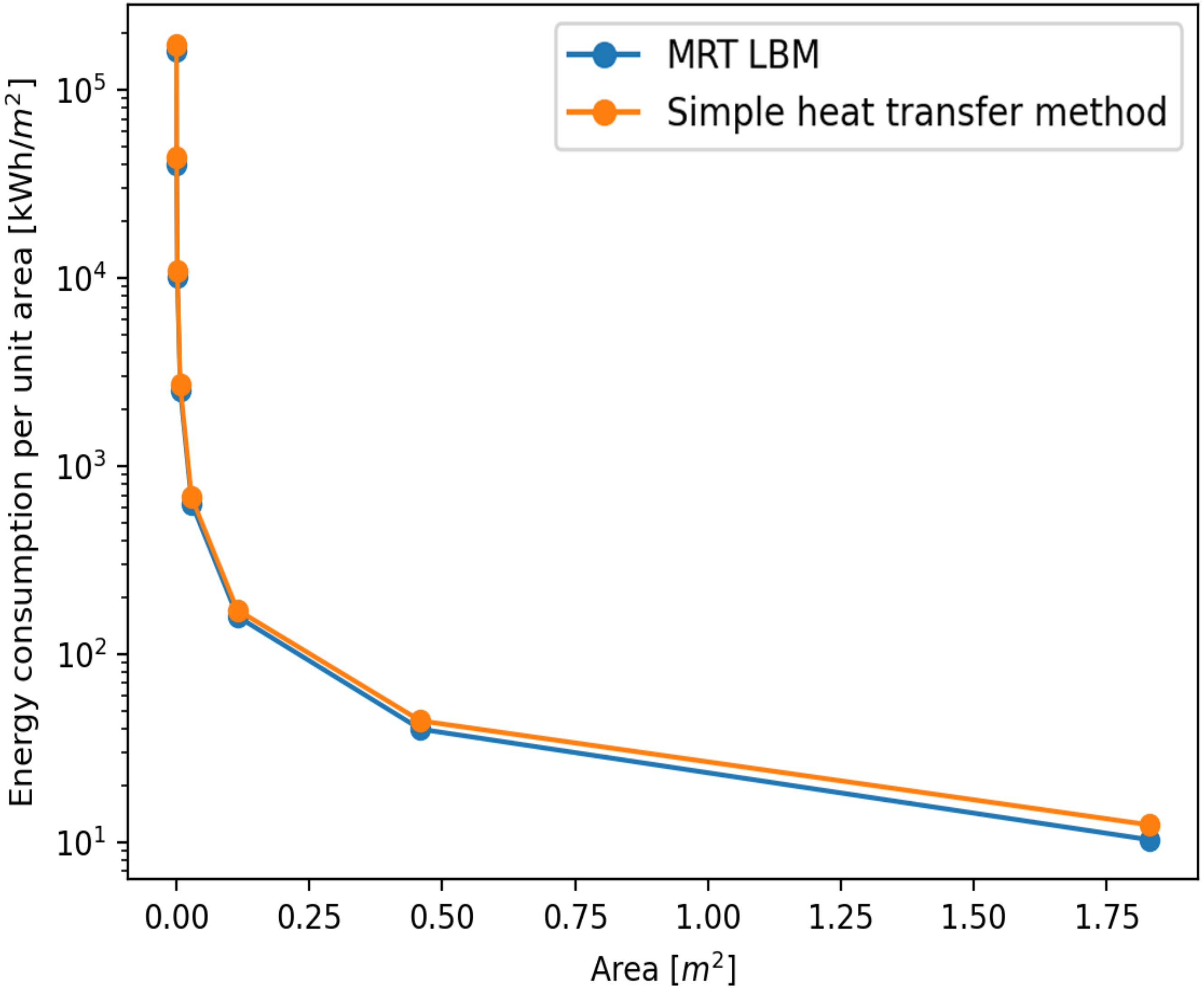
Results: What-if Analysis

Influence of Design and Process Parameters

- Loading autoclave to its maximum capacity is more energy efficient



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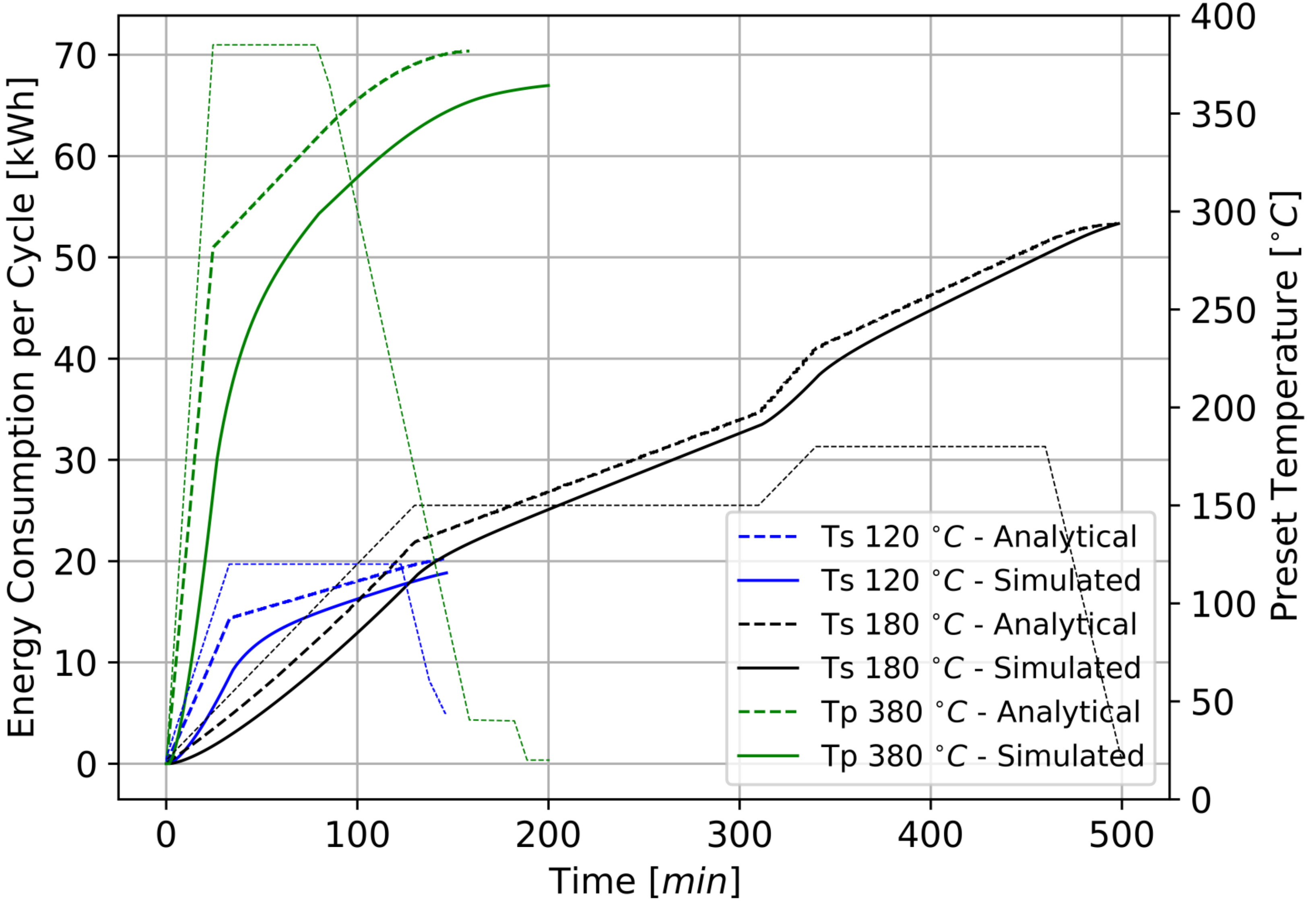
Results: What-if Analysis

Influence of Design and Process Parameters

- ✓ Cure temperature influence energy consumption
- ✓ Cycle time also influence energy consumption
- ✓ Thermal mass dominate for short cycles
- ✓ Thermal mass and heat losses dominate for short cycles



Conclusion

- ✓ Autoclave curing is a major contributor to energy consumption of CFRP Manufacturing
  - Energy Efficiency of Autoclave curing lies below 3%
- ✓ Thermodynamics based models can be used to create energy estimates of autoclave curing
  - Code readily available under MIT license (Please scan QR code)
  - Model can be used in autoclave design optimisation, process optimisation, energy inventory especially in aerospace industry where data is proprietary and isn't readily available.
- ✓ Autoclave thermal mass and heat losses are major contributors to energy consumption of autoclave curing.

Models for Estimating Energy Consumption

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Thank You