A WEBINAR ON:

DECONSTRUCTING COMPOSITES PROCESSING

Why it seems so complex and how to think about it in a structured way

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YOUR HOSTS

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- Ph.D. and M.A.Sc. in Composite Materials Engineering
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- Expertise in liquid composite moulding and thermal management

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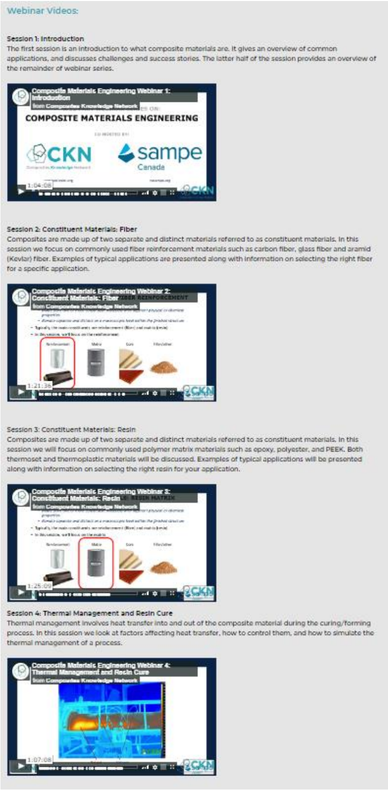


Outline

- Why composites manufacturing may seem complex
- Systems approach to composites manufacturing
  - A structured way to think about manufacturing
- Case study
  - Application of the systems approach
- Special announcement

Why does composites manufacturing seem so challenging?

Is it really that complex?

Common complexities associated with composites manufacturing

- Multiple different materials, each with their own properties
  - Fibres, resin, core, tooling, etc.
- Orthotropic nature of composite
  - Material properties are direction dependent
- Many different material forms
  - Continuous vs discontinuous
  - Uni-directional vs woven vs random mat
  - Prepreg vs non-prepreg
  - Thermoset vs thermoplastic
  - Sandwich panel vs laminate
- Exothermic heat released during cure
- Part construction heavily influences final properties
- Tooling considerations
- Equipment considerations
- Strict regulations (particularly in aerospace)
- And more...

Source: freepik.com

Manufacturing processes…traditionally

- Many different manufacturing processes
  - RTM
  - VARTM
  - Spray-up
  - Wet layup
  - Pultrusion
  - Filament winding
  - AFP/ATL
  - Autoclave processing
  - Out-of-autoclave processing
  - Compression moulding
  - Bladder moulding
  - And more…

- Common to think of these composite manufacturing workflows as unique
- Only describes a portion of the entire workflow
- More similarities than differences between each "process"
- Capturing these similarities and differences and describing them systematically is what's important

Systems approach

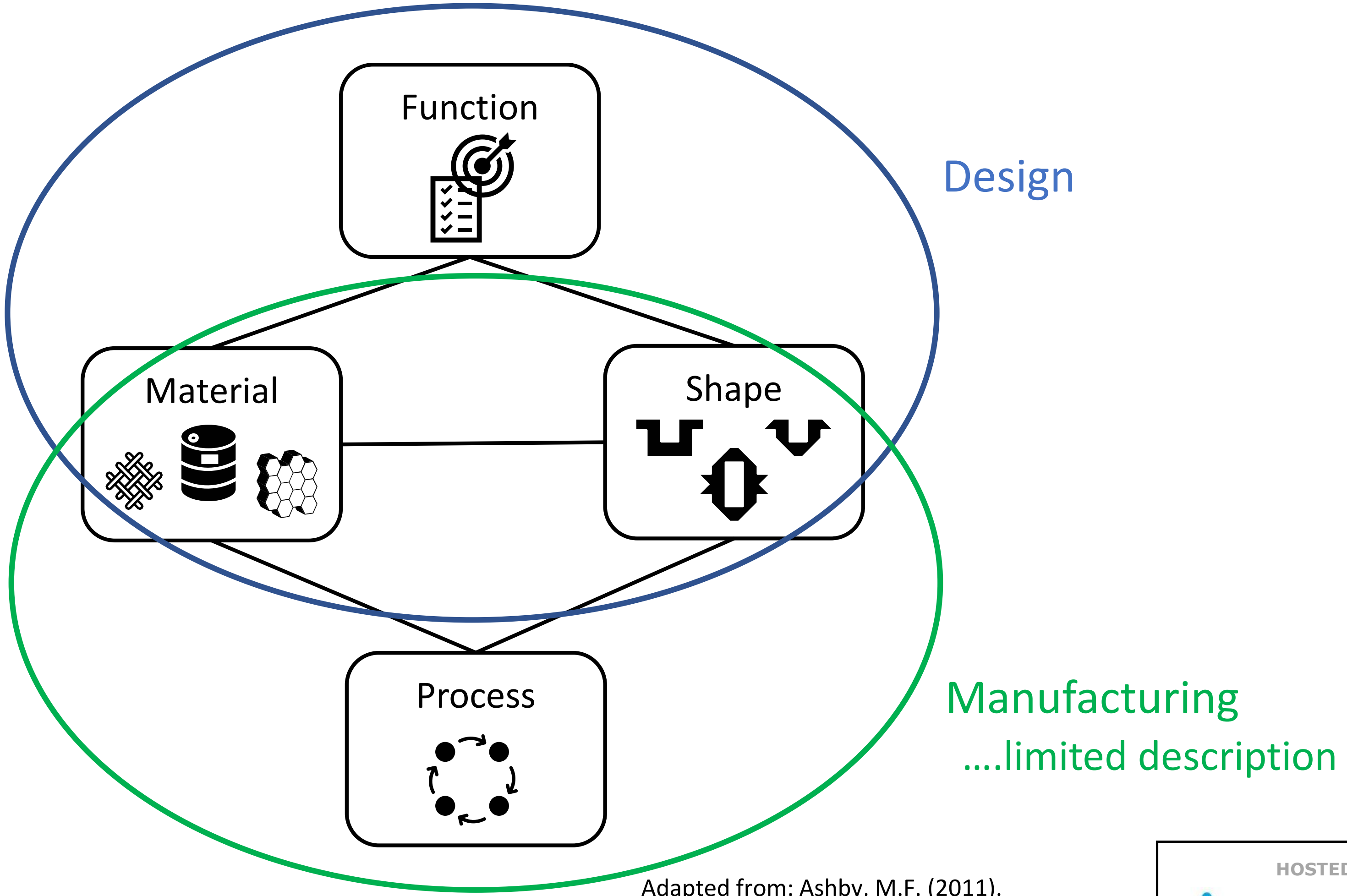
A structured way of thinking about composites manufacturing

Builds on doctoral work by Dr. Janna Fabris, under the supervision of Dr. Anoush Poursartip:
https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0372787

Fabris, Janna Noemi (2018).

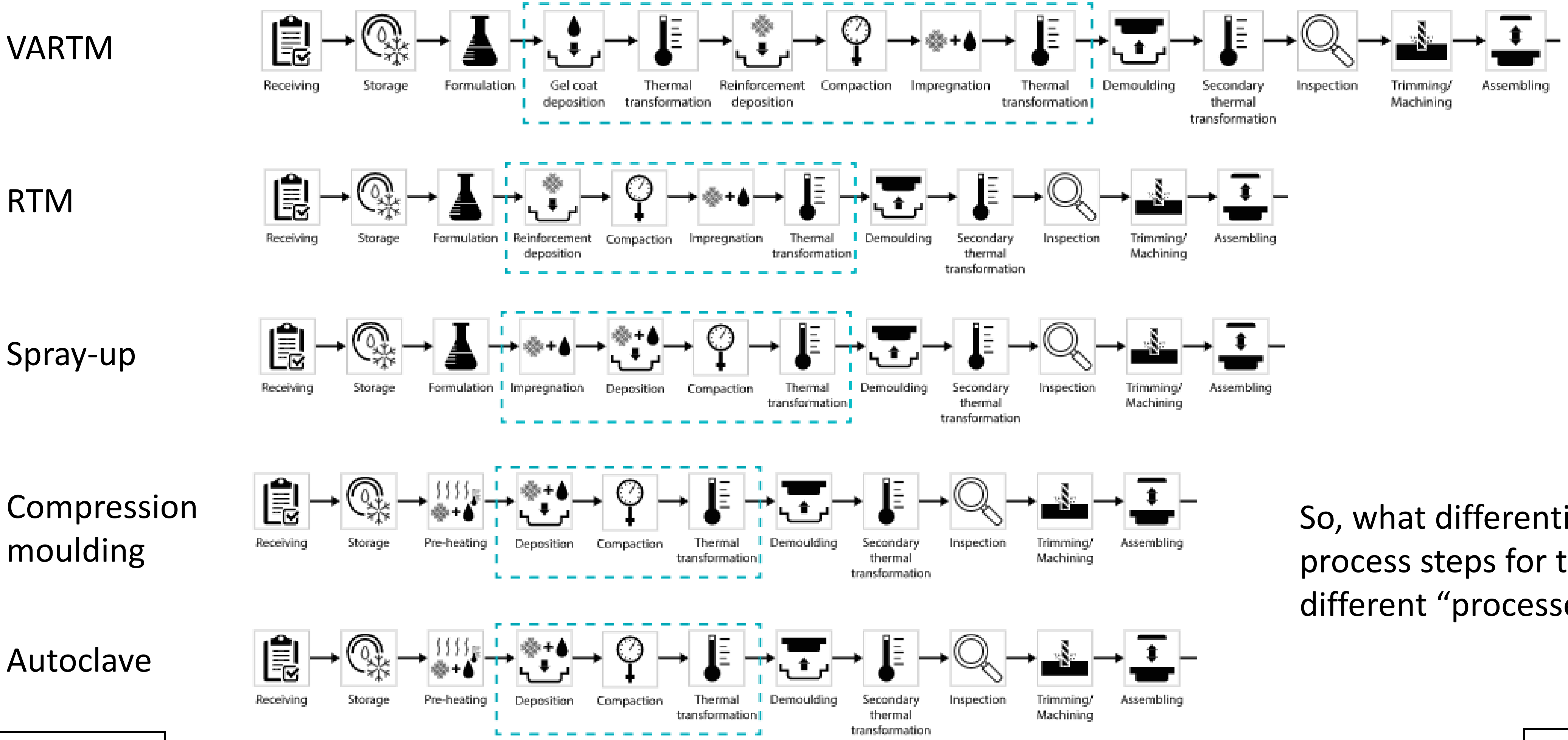
Design and manufacturing

- Traditionally, engineering design is dictated by the interplay between:
  - Part function
  - Part material
  - Part shape
  - Manufacturing process



Adapted from: Ashby, M.F. (2011).

A process is really a collection of steps



So, what differentiates the process steps for the different “processes”?

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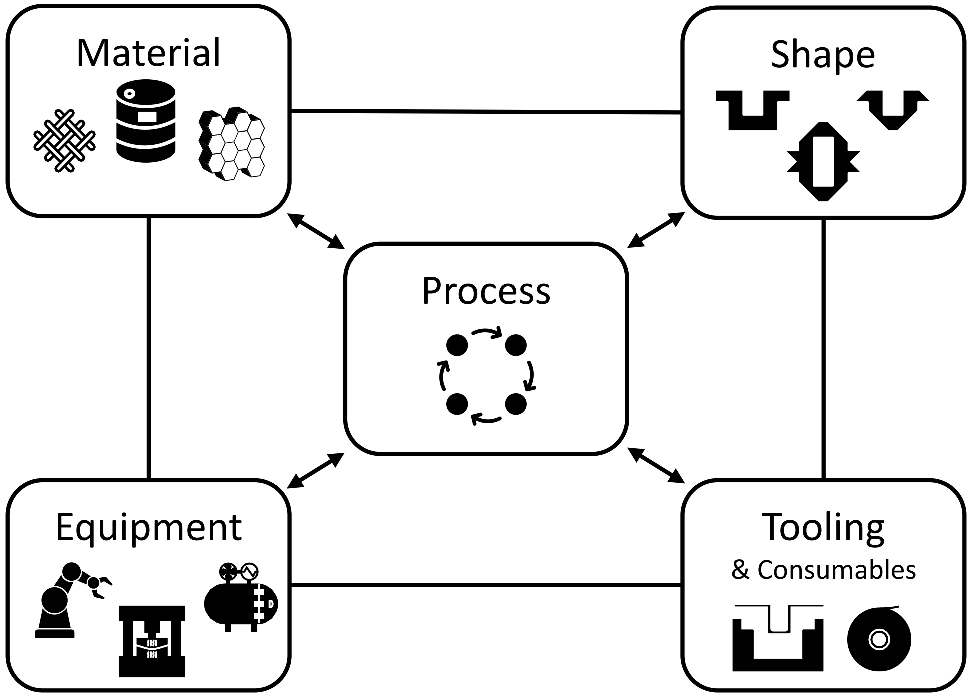
Describing a manufacturing process

- Each process requires some level equipment and tooling.
- In order to fully define the process, the equipment and tooling must be defined for each step.
- The equipment and tooling needed are based on the part's raw material and desired shape
- Together, the material, shape, tooling, and equipment define the process
- This is true for all process steps in a factory



Adapted from: Fabris, Janna Noemi (2018).

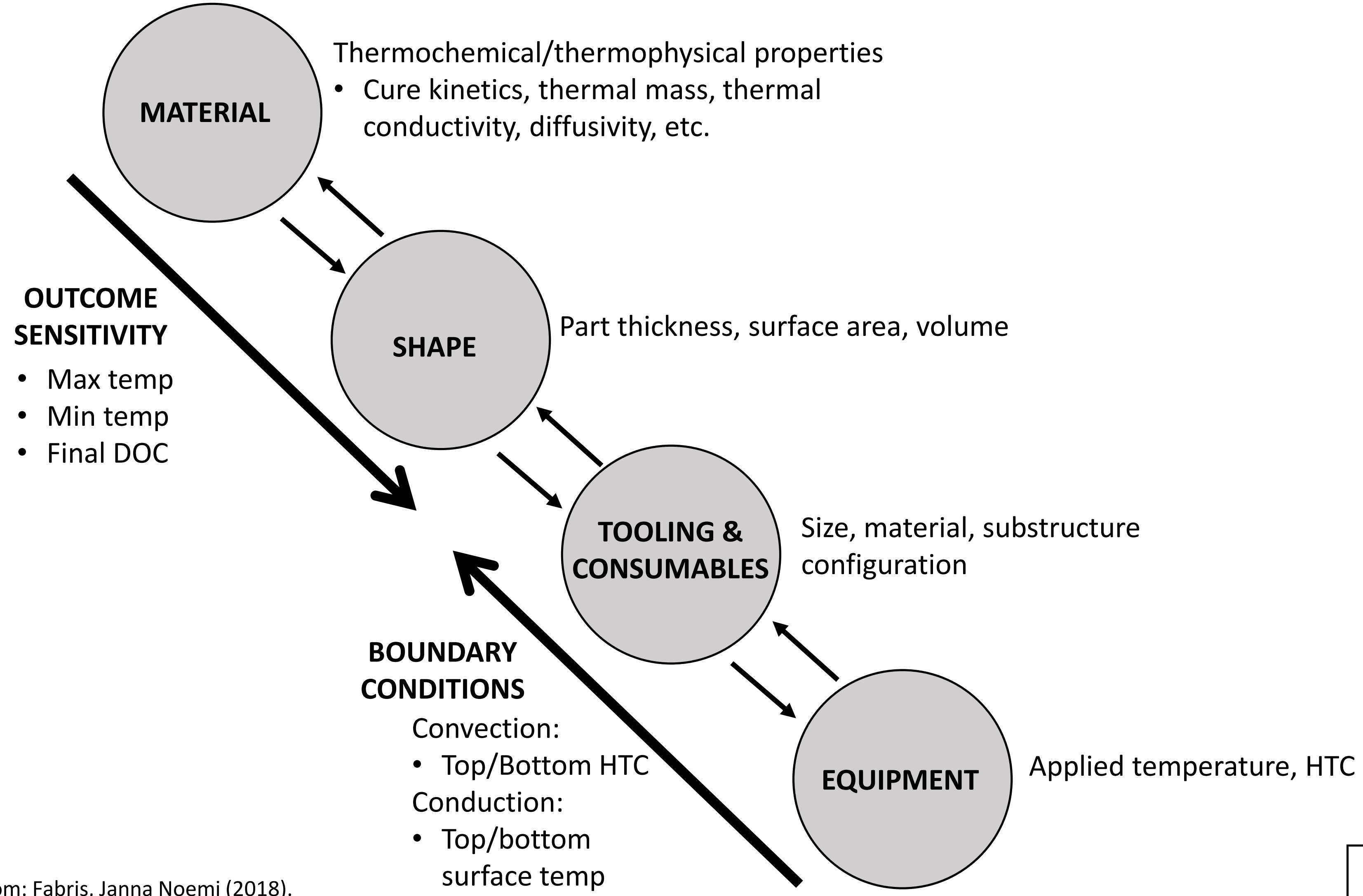
What does this mean? How is this useful?

- Every process in a factory can be thought of as a system of interacting components between the material (M), shape (S), tooling and consumables (T), and equipment (E)
  - Known as the MSTE interactions
- Each component plays a role in influencing the process outcomes
- Easy, logical way to think about each process – answers the "What" of composites processing
  - Eg:
    - What materials am I using, what are the relevant material properties?
    - What is the geometry of the part? Is it thick or thin?
    - What kind of tooling material am I using? What is its geometry?
    - What equipment am I using, what are its processing conditions?

MSTE interactions

- The nature of interactions between MSTE components can be classified into themes depending on the outcome(s):
  - Thermal management (TM)
    - Achieve proper temperature
      - Gelation time, DOC, Tg
  - Material deposition management (MDM)
    - Get the raw material on the tool (part construction)
      - Fibre volume fraction, laps/gaps, resin rich/starved areas
  - Flow and consolidation management (FCM)
    - Ensure proper quality once the materials starts flowing
      - Fibre volume fraction, wrinkling, porosity, core movement/crush
  - Residual stress and dimensional control management (RSDM)
    - Ensure dimensional stability
      - Spring-in, cure shrinkage, cracking, warping, delamination

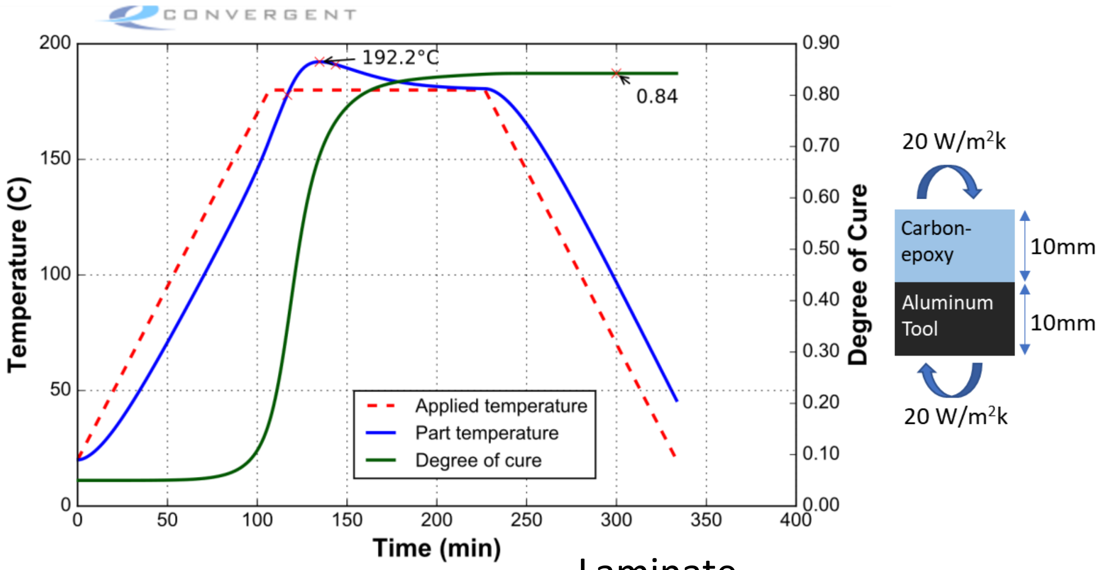
E.g. Thermal management interactions



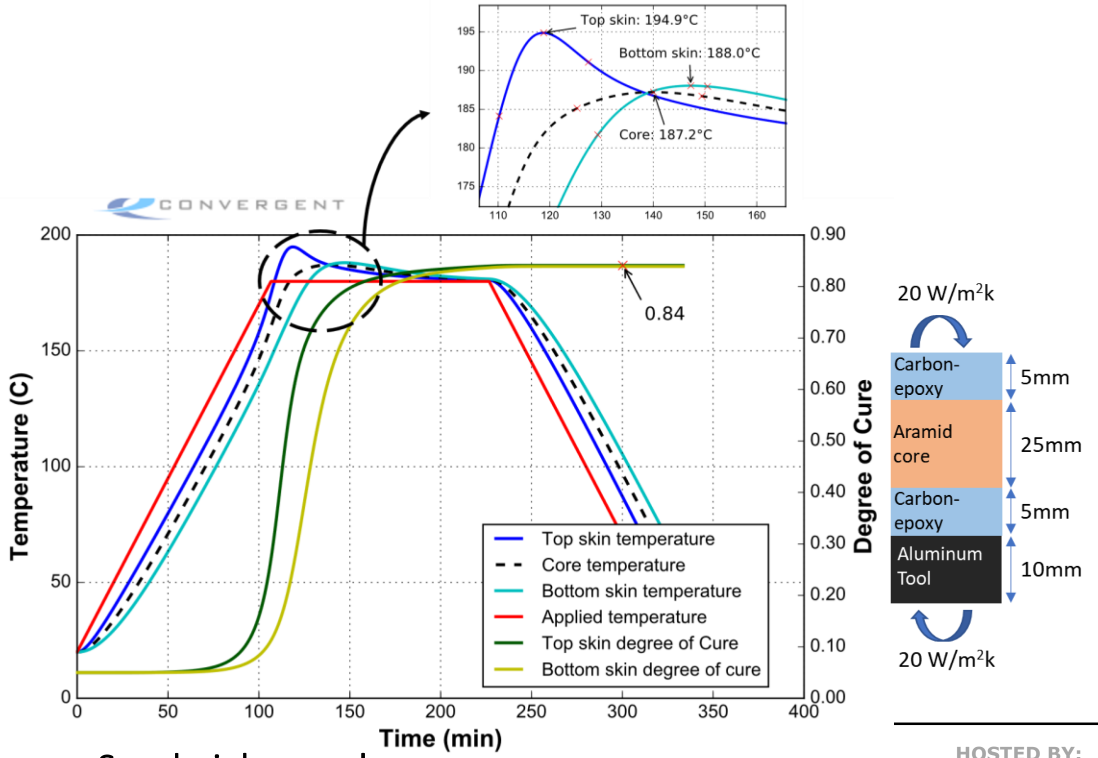
Adapted from: Fabris, Janna Noemi (2018).

Effect of material in a thermal management system

- Material type
  - Carbon vs glass, epoxy vs polyester
    - Degree of cure, glass transition temperature, exotherm, density, thermal mass, thermal conductivity, thermal diffusivity, etc.
- Material form
  - Weave pattern, sandwich panel vs laminate
    - Fibre volume fraction, exotherm, thermal lag, etc.



Laminate



Nomex Sandwich panel

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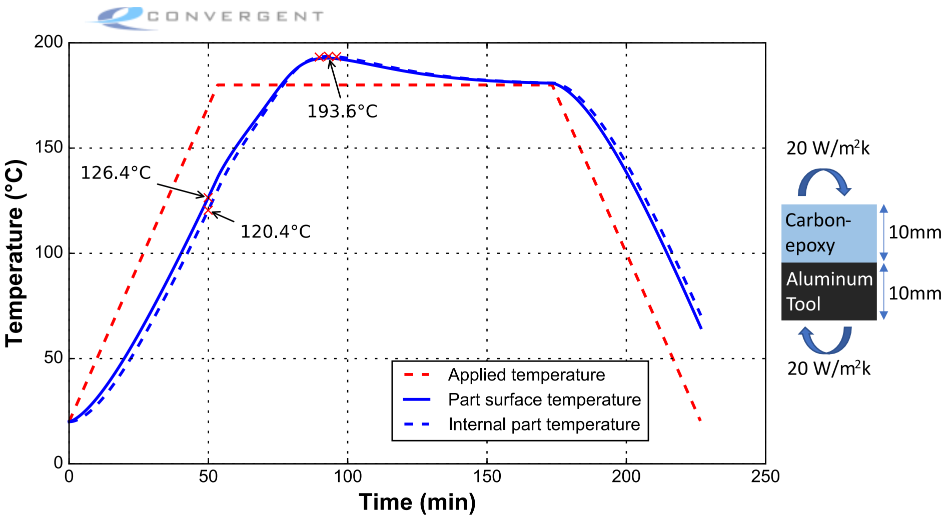
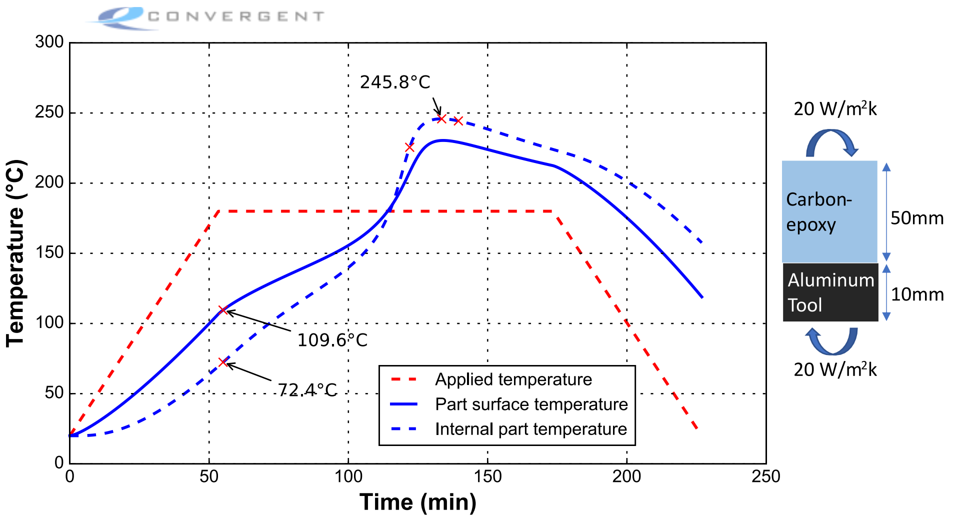
Effect of shape in a thermal management system

- Thickness:
  - Thicker parts have a larger thermal mass - require more energy to heat up
    - Increases thermal lag and part exotherm



10mm part



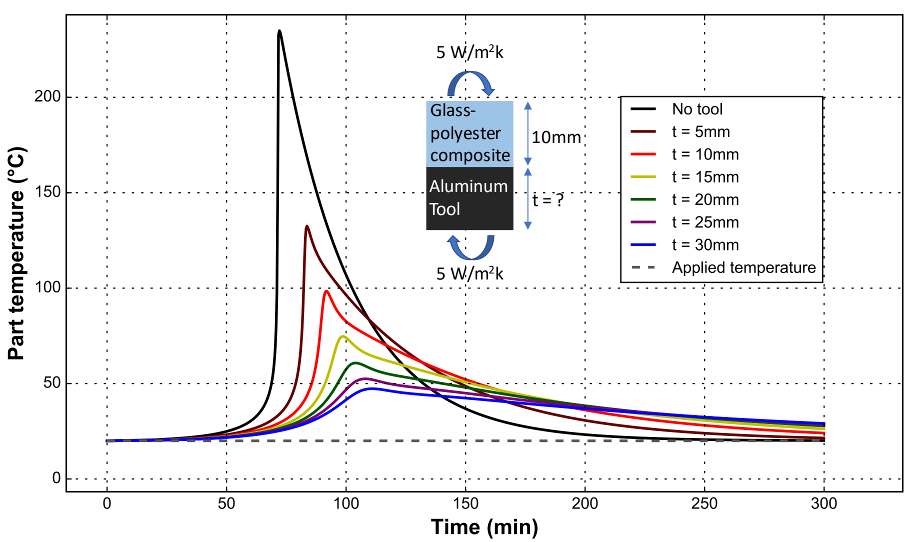
50mm part

- Configuration
  - The size and shape of the part can influence airflow which affects the heat transfer coefficient (HTC)

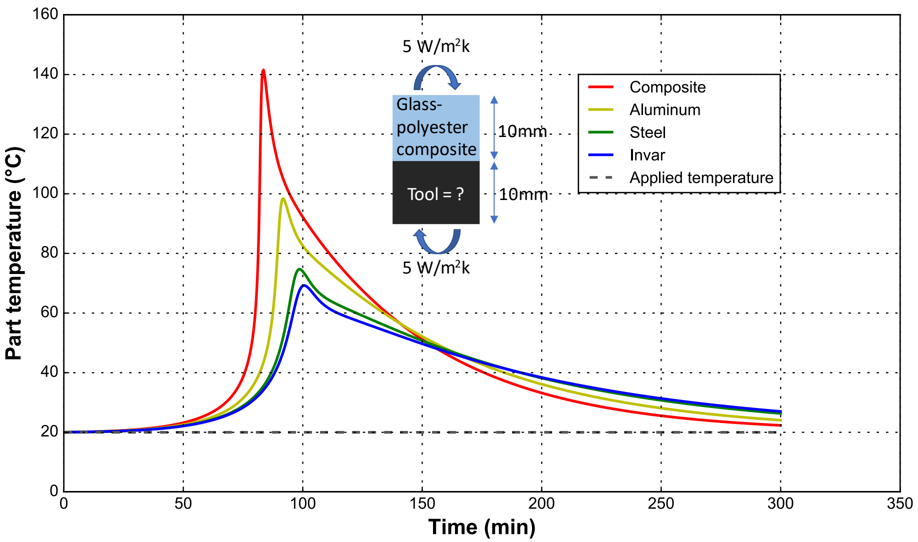
Effect of tooling in a thermal management system

Effect of tooling:

- Thickness:
  - Similar to part shape a thicker tool will have a larger thermal mass and require more energy to heat up (but also to cool down)
- Material:
  - Influences thermal mass and properties such as conductivity and thermal diffusivity



Changing tooling thickness – room temp cure



Changing tooling material – room temp cure

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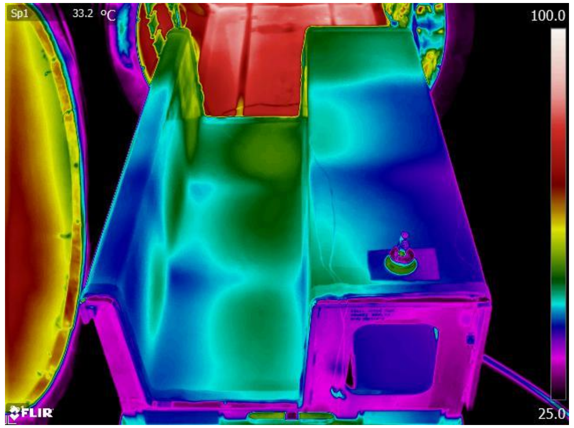
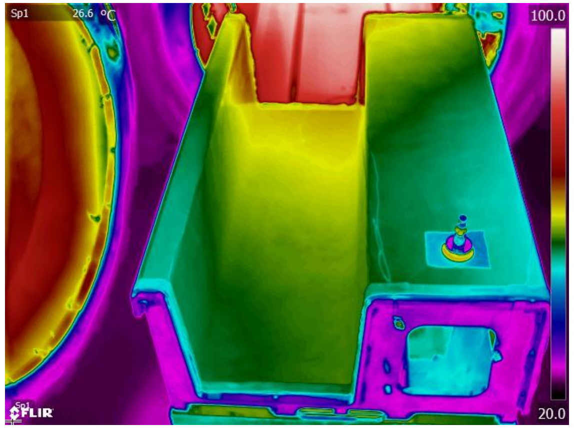
Effect of tooling in a thermal management system cont.

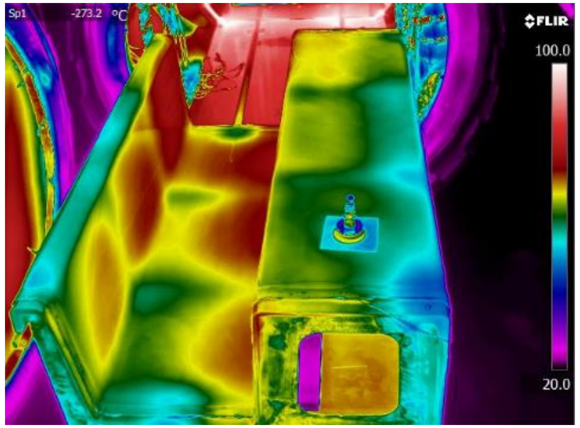
- Material



Invar



Aluminum

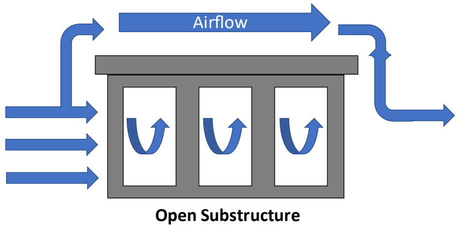


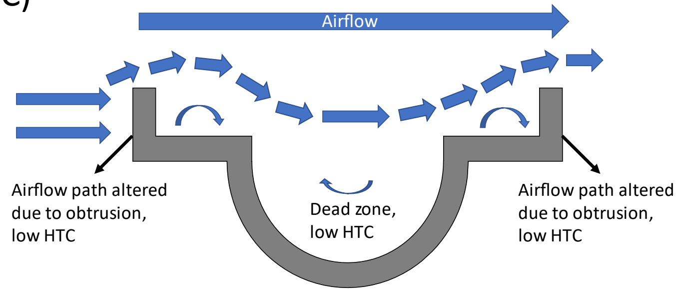
CFRP composite

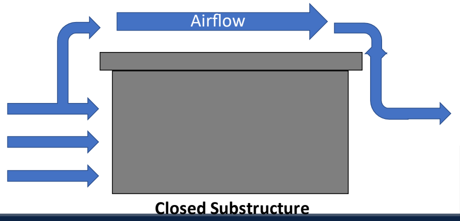
100°C

20°C

- Tooling configuration is another parameter to consider
  - Tool shape and substructure can influence airflow
    - Affects heat transfer coefficient (HTC)
  - Part shape can also be a factor







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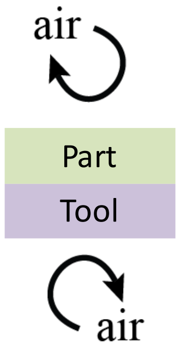
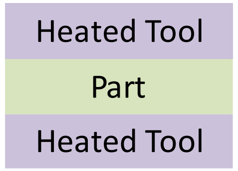
Effect of equipment in a thermal management system

- The equipment controls the processing environment for the entire tool/part assembly.
- Heating may either be convective or conductive (boundary conditions)
- For convective heating, heat transfer occurs through motion of air particles
  - Heat transfer coefficient (HTC) important
- For conductive heating, heat transfer occurs through direct contact with the tool-part
  - Temperature at tool-part surface important



$$-k\frac{\partial T}{\partial z} = h(T_{air} - T_{surface})$$

Convective heating boundary

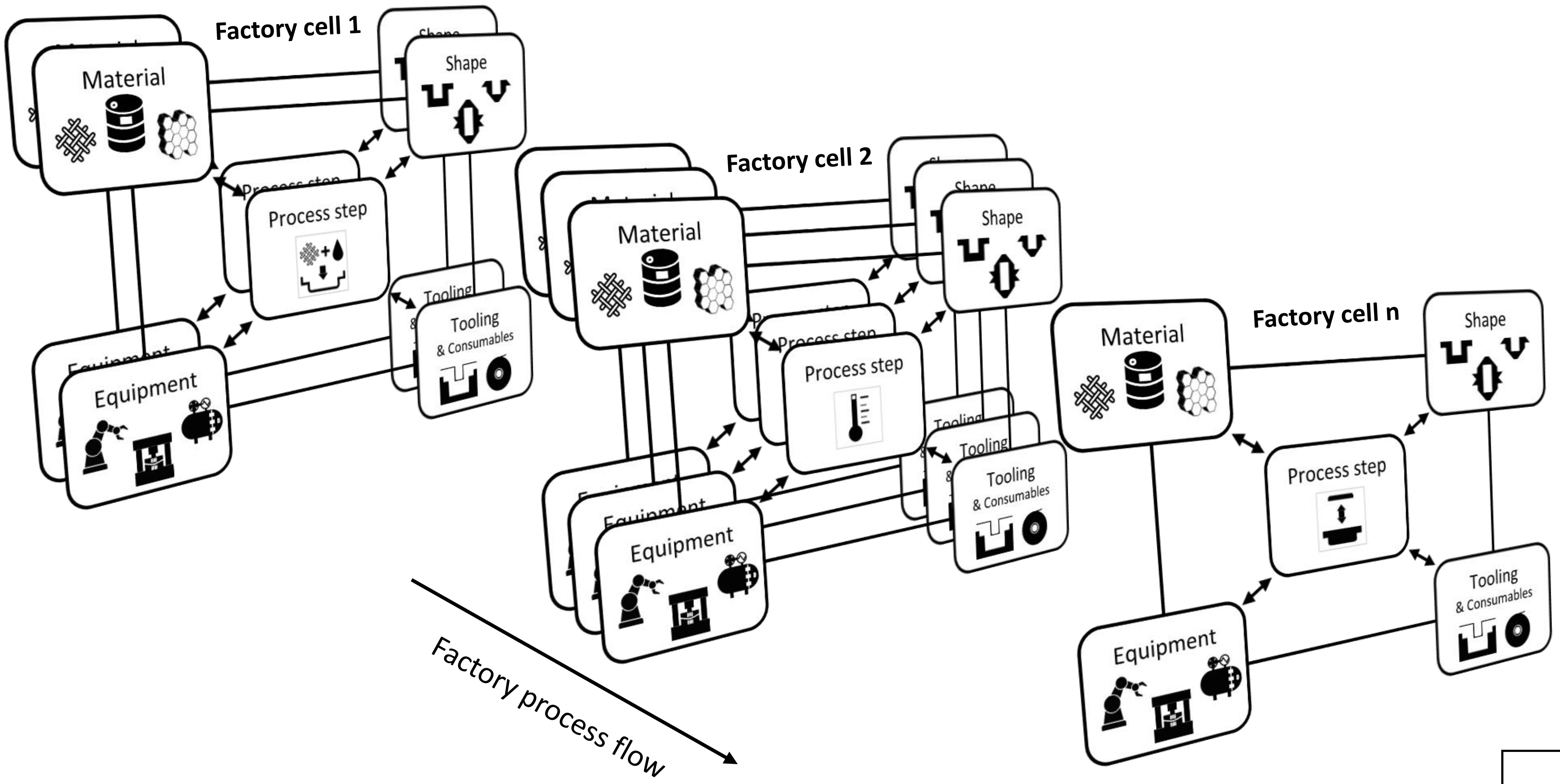


$$T_{surface} = T_{tool}$$

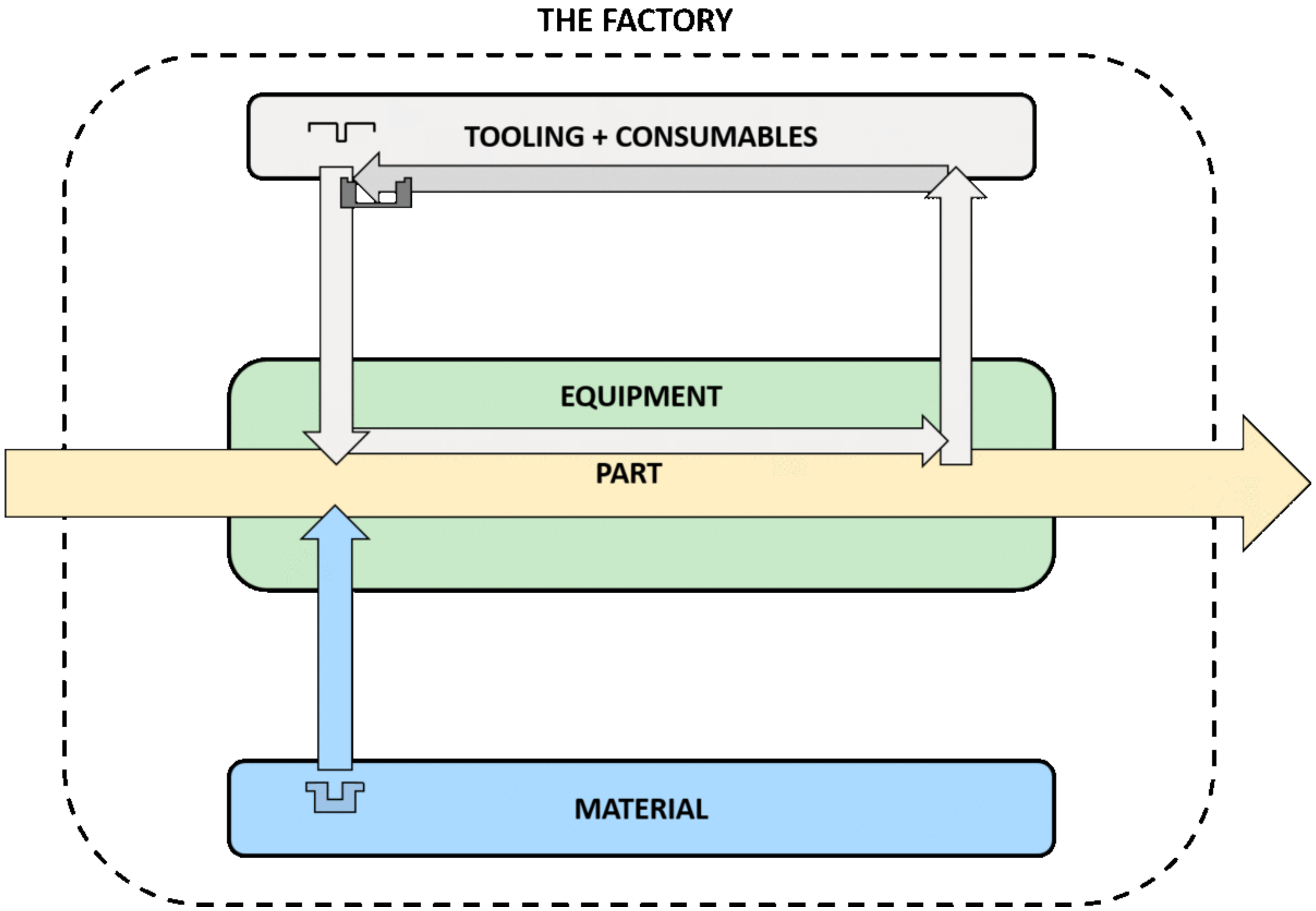
Conductive heating boundary

How does this all come together in a factory?

- Process steps must occur within physical spaces in the factory – factory cells



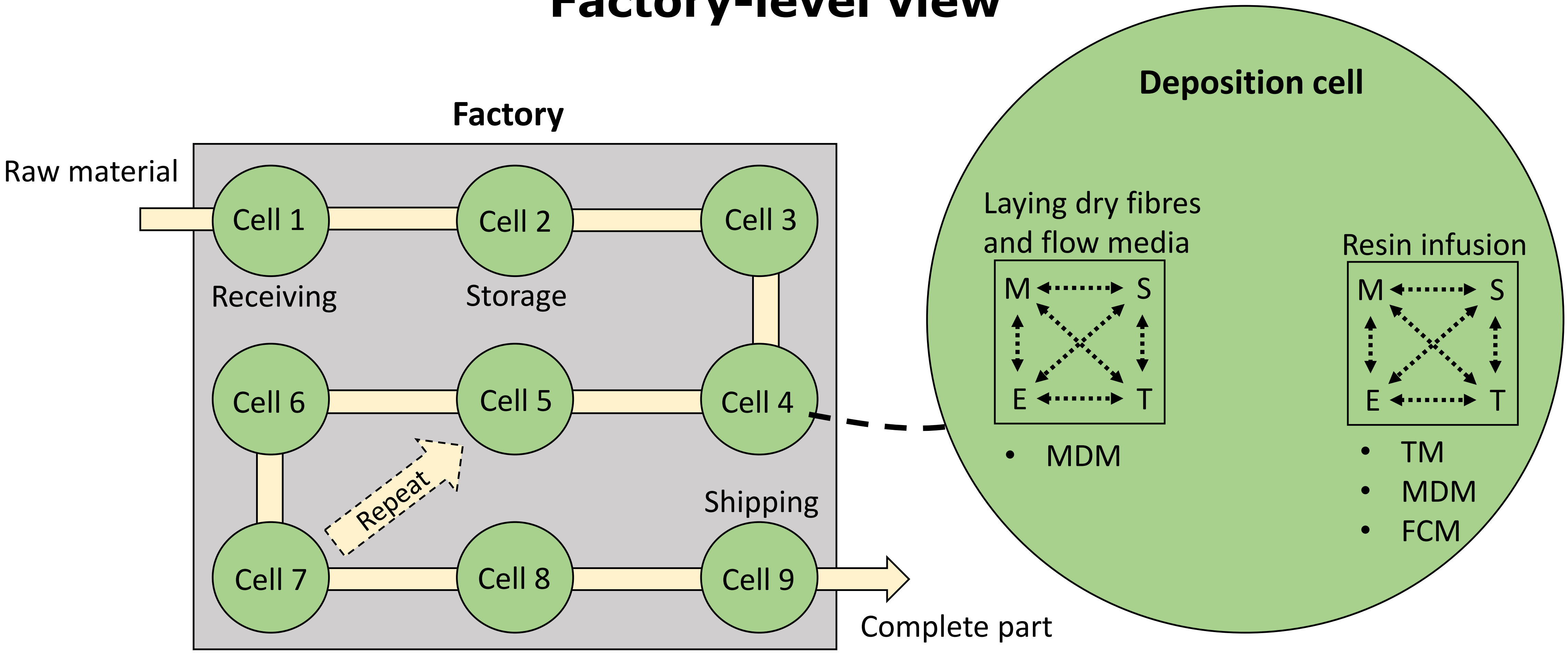
Factory-level view



Adapted from: Fabris, Janna Noemi (2018).

- Raw **material** comes into the factory at various stages and flows through various factory cells
- **Tooling** is brought in and out of cells to **shape** the material into the part
- The part/tool passes through **equipment** in each cell of the factory
- Eventually a final part is output

Factory-level view



Factory-level view

- Don't only need to think about flow of raw material through factory, but also tooling, equipment, and people
- The factory layout is important for processing efficiency, part quality, ability to scale-up, and safety
- Better to think about these things early, during the conceptual design phase

What governs manufacturing decisions?

- Manufacturing processes must achieve acceptable:
  - Quality
  - Cost
  - Rate
  - Environmental impact

Defined by manufacturer, customer, or regulations

Essence of composites manufacturing practice

- These must be managed during:
  - Development
    - Moving towards production
  - Optimization
    - Improving working processes
  - Troubleshoot
    - Fixing processes that aren't working

Workflow might look different

For all, must get these right:
TM, MDM, FCM, RSDM

Workflows

Development:

- Not yet production-ready
- Must meet quality, cost, rate, environmental metrics
- Workflow centres around demonstrating new MSTE systems meet metrics

Optimization:

- May be in production
- Quality, cost, rate, or environmental metrics are met but want to improve one or more of them
- Workflow centres around improving existing MSTE systems

Troubleshooting:

- May be in production
- Quality, cost, rate, or environmental metrics are not being met
- Workflow centres around altering existing MSTE systems

Case study

Troubleshooting of room temperature processes for large recreational and industrial parts

Background and problem definition

Background

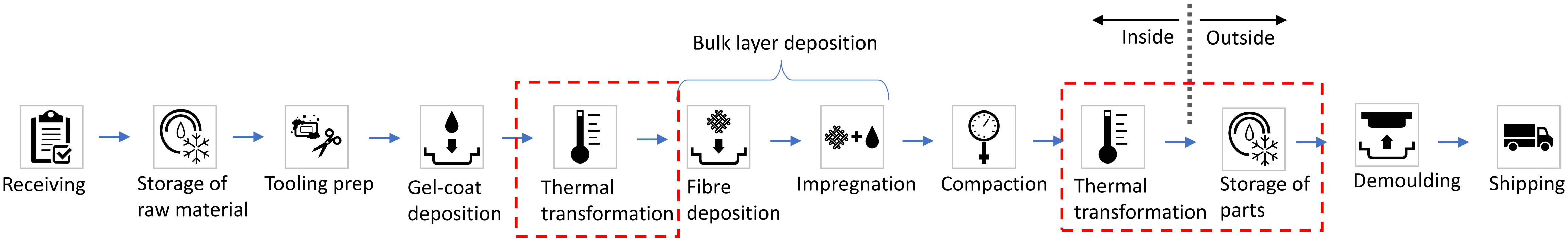
- Several companies in BC reported issues with inconsistent product quality depending on the season in which they were manufactured.
- Parts were cured at *ambient* air temp
- Glass fibre-polyester used - sourced from same manufacturer in each case

Problem definition

- Workflow: Troubleshooting
- Objective: Improve part quality without detriment to cost, rate, or environment

Which process(s) are causing the defects?

- List defects
  - Discolouration, deformation upon demoulding, poor surface finish, reduced durability
- Identify common outcomes that may be responsible for defects (if known)
  - Inconsistencies in degree of cure (DOC) ⟶ **Thermal management problem**



Which process steps may be the problem?

- Are there any steps where the MSTE parameters are not controlled or have been changed?
  - E.g.: Material operating outside specifications, changes to the part shape, changes to the tooling and consumables, fluctuations in environmental conditions, etc.

In this case, we know part quality is tied to the season and the DOC is suspected to be the problem

All of this points to potential problems arising during thermal transformation (cure)

- For room temperature processes, curing begins once resin is mixed and may continue afterwards.

List MSTE objects in each step

- Thermal transformation of gel coat:
  - M = gel coat (polyester resin)
  - S = thin layer
  - T = CFRP mould
  - E = Indoor room

- Outdoor storage
  - M = glass fibre-polyester composite
  - S = Variable thickness depending on part
  - T= CFRP mould
  - E = Outdoor environment

- Thermal transformation of bulk layer:
  - M = glass fibre-polyester composite
  - S = Variable thickness depending on part
  - T= CFRP mould
  - E = Indoor room

- Troubleshoot each step one by one to see if there is indeed a problem and what mitigation strategies may be implemented.
- Goal is to improve quality without major investment in cost, rate, environmental impact

1. Thermal transformation of gel coat

M = Gel coat (polyester resin)

S = Thin layer

T = CFRP mould

E = Indoor room

What can be improved and/or changed without altering the process too much?

E: Gel coat is subject to room temperature and airflow fluctuations. Temp = 15-17°C.

- Could add improved HVAC system to control temp/airflow/humidity

T: Low thermal mass (heats up quickly), low diffusivity (may have hot/cold spots).

- Could change tooling material/geometry

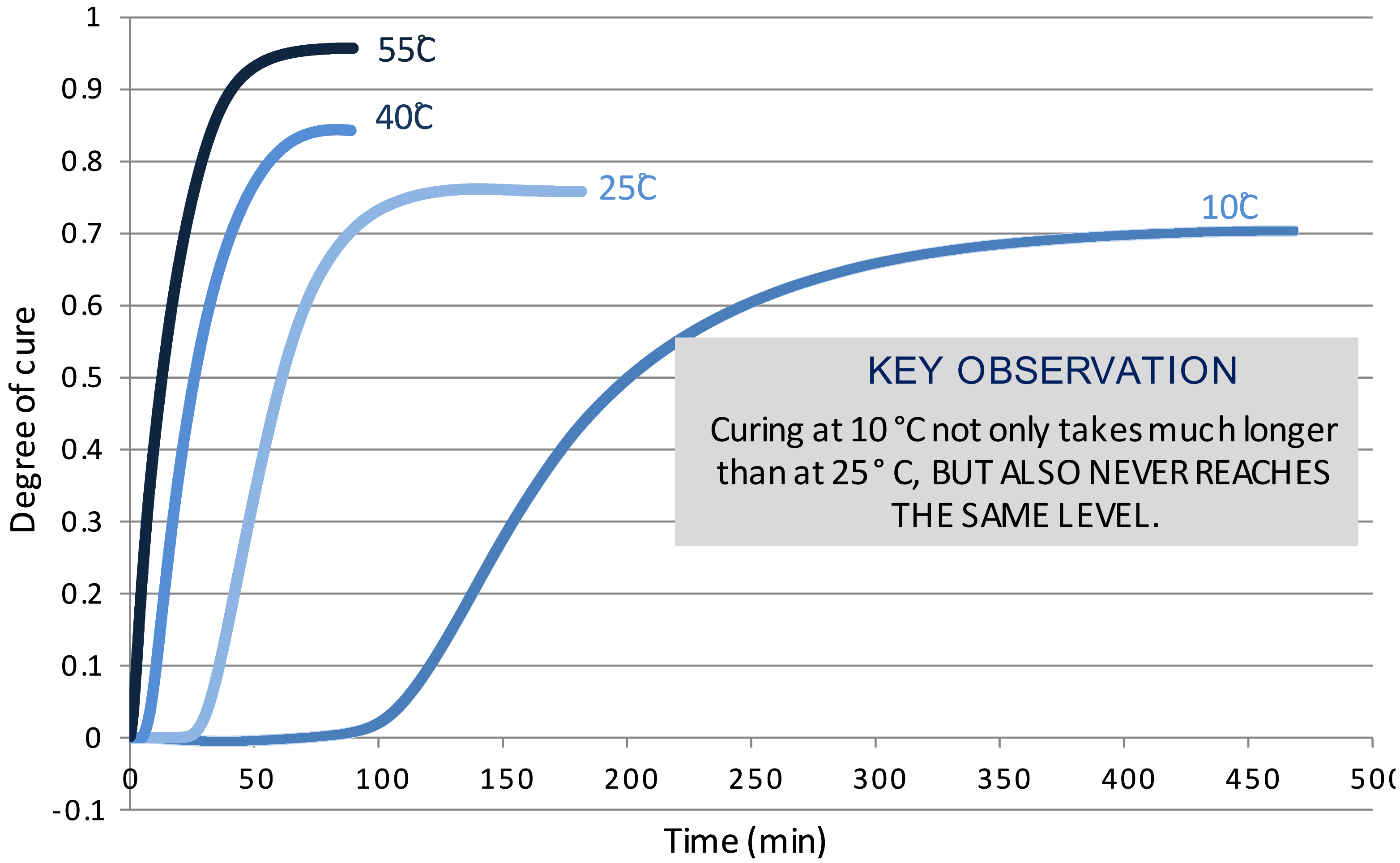
S: Gel coat layer is intended to be thin - can't change much.

M: Depending on time/temperature, DOC will advance differently. Important to achieve moderate (but not too high) DOC before adding bulk layer.

- Investigate cure kinetics to improve timing of bulk layer deposition

M: Cure kinetics of polyester

DSC tests conducted to investigate resin cure kinetics



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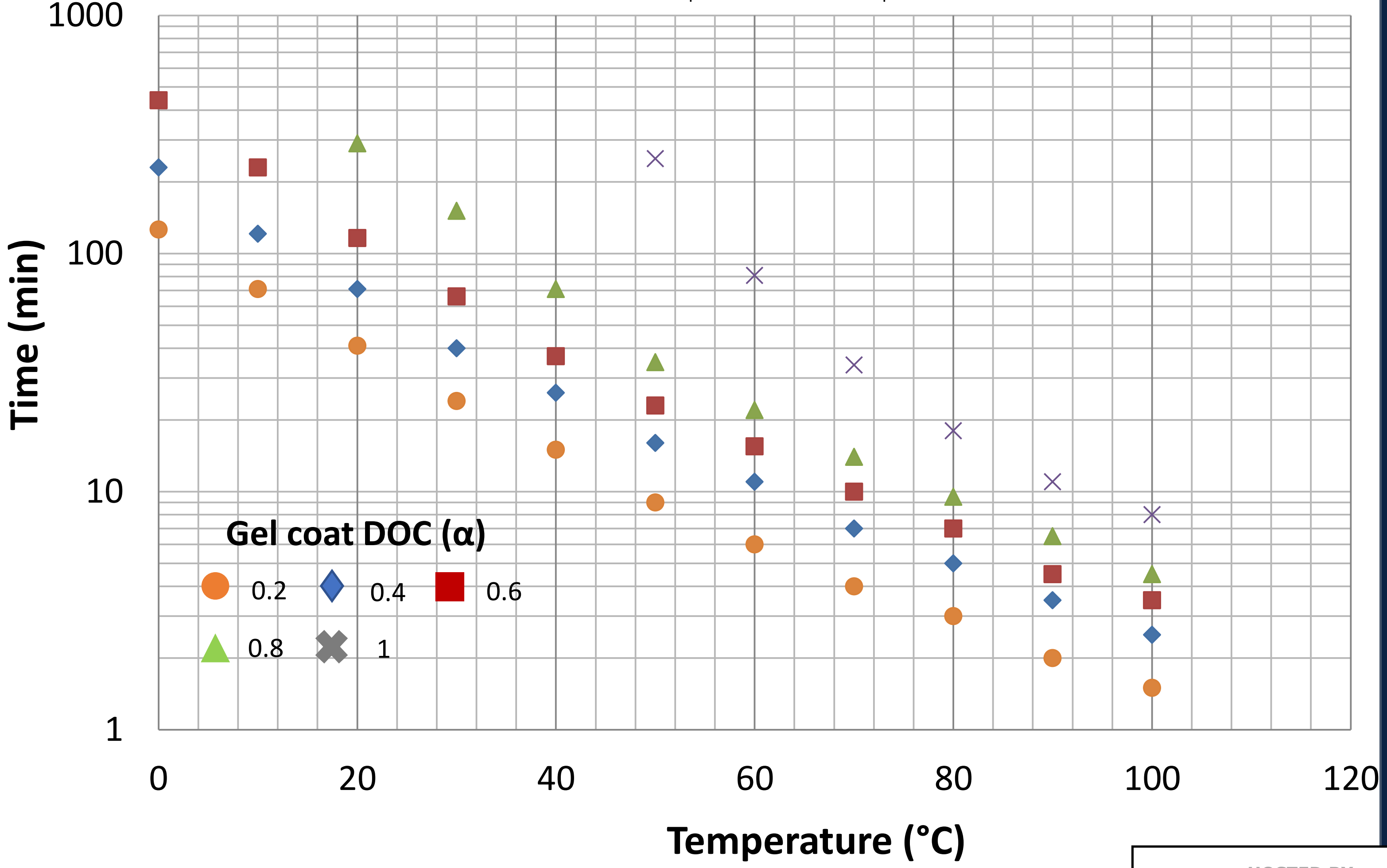
M: Timing DOC of gelation and addition of bulk layer

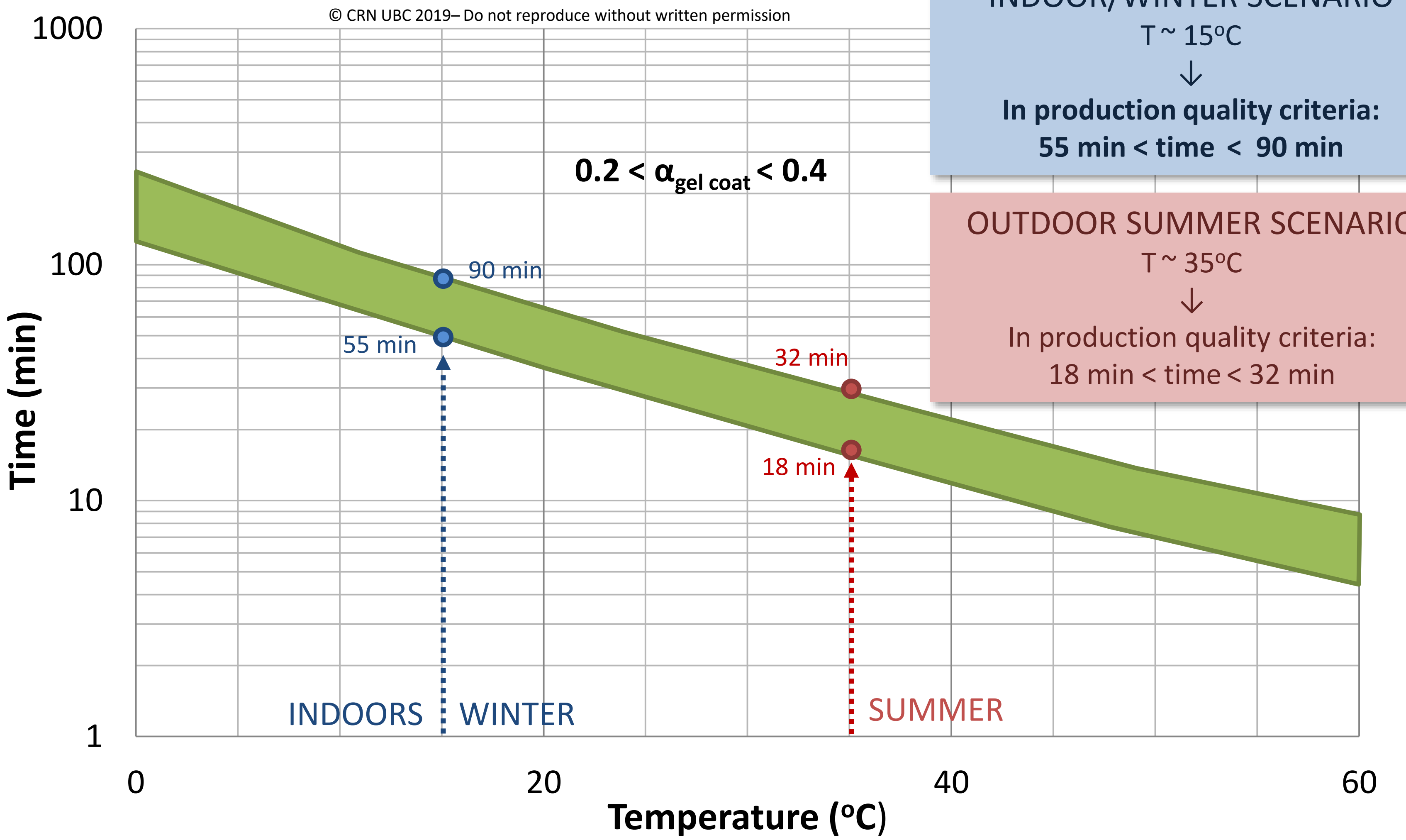
- Gelation of polyester resin ~ 0.1

- Want to time bulk layer deposition once gel coat has achieved gelation but not much further

0.2 <α <0.4



M: Timing DOC of gelation and addition of bulk layer



INDOOR/WINTER SCENARIO
T ~ 15°C
↓
In production quality criteria:
55 min < time < 90 min

OUTDOOR SUMMER SCENARIO
T ~ 35°C
↓
In production quality criteria:
18 min < time < 32 min

2. Storage of part outdoors

What can be improved and/or changed without altering the process too much?

M = Glass-polyester

S = Variable thickness

T = CFRP mould

E = Outdoor environment

E: Daily weather (temperature, humidity, wind). Temp = variable.

- Investigate temperature variability
- Can insulate part from environment → Discussed later

T: Low thermal mass (heats up quickly), low diffusivity (may have hot/cold spots).

- Could change tooling material/geometry

S: Part thickness will influence amount of exothermic heat

- Specifications to achieve same DOC for variety of thicknesses → Discussed later

M: DOC is a function of time and temperature

- Investigate whether placing parts outdoors after indoor processing influences the final degree of cure of the part

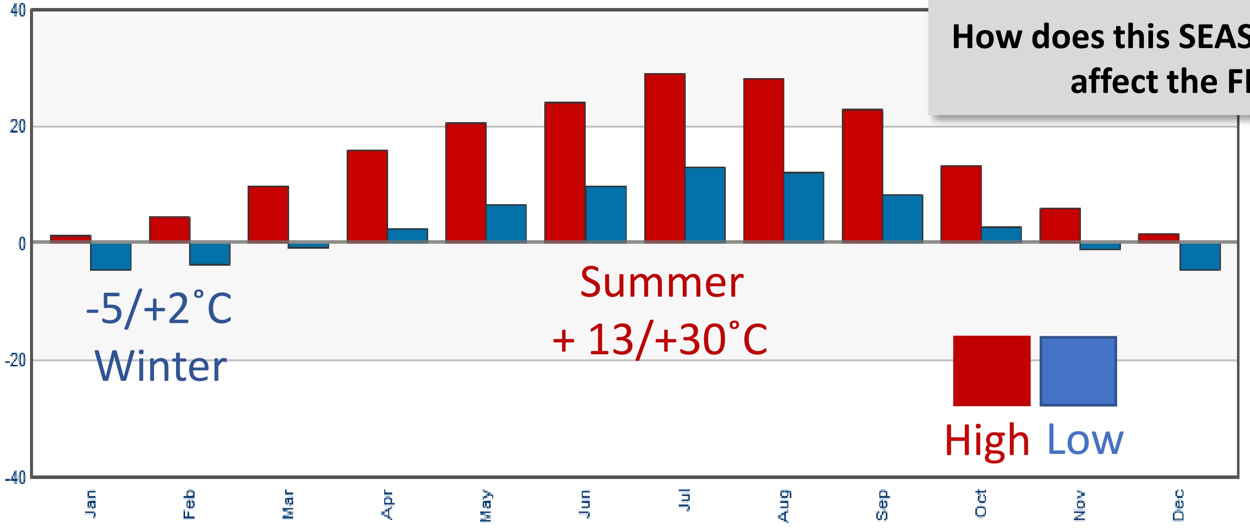
E: Investigate variability in processing conditions

- Outdoors, parts are exposed to daily and seasonal weather patterns

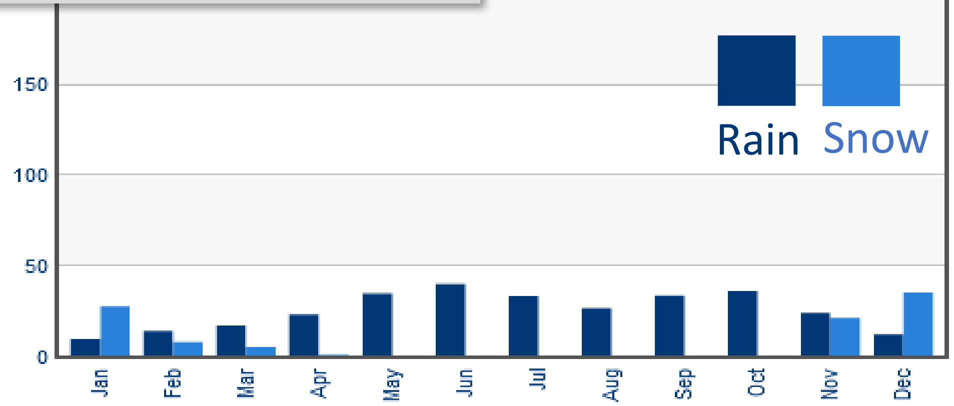
KEY OBSERVATION

Significant temperature variation through the seasons.

How does this SEASONAL CHANGE in temperature affect the FINAL DEGREE OF CURE?



Temperature

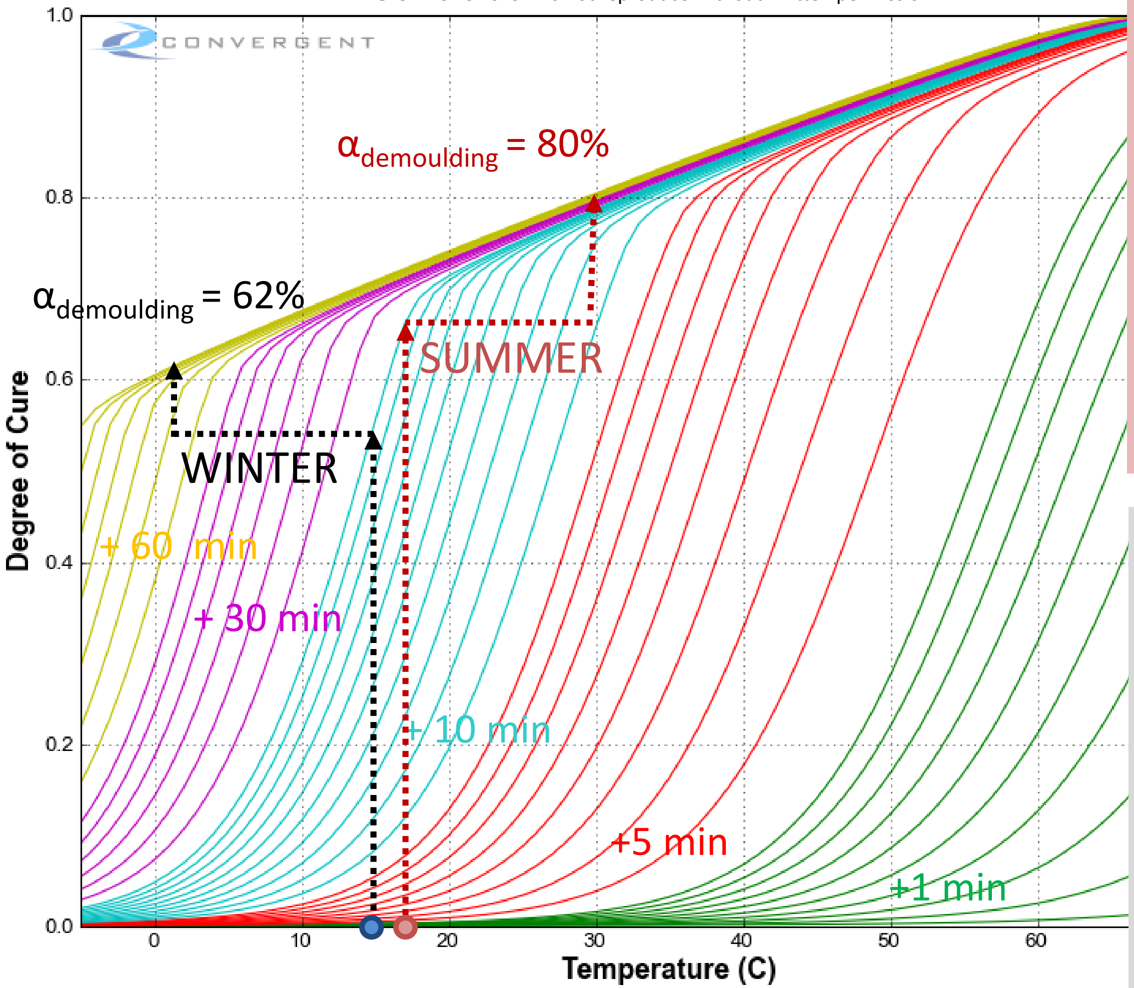


Precipitation

* The Weather Network [31/08/2011] http://www.theweathernetwork.com/statistics/temperature/cl11239r0/cabc0149

M: Investigate cure kinetics to understand summer vs winter scenarios on DOC

- Performed analytical tests to establish a cure kinetics map
- After processing indoors, parts continue to cure outdoors
- Thermal transformation actually extends to both an indoor and outdoor environment
- Parts are subject to daily and seasonal temperature fluctuations
- Mitigation strategy:
  - Cure parts fully at higher temperature



SUMMER SCENARIO

A) Morning – $T_{workshop}$ = 17°C

↓

B) Afternoon – $T_{outside}$ = 30°C

↓

$\alpha_{demoulding}$ = 80%

WINTER SCENARIO

A) Morning – $T_{workshop}$ = 15°C

↓

B) Afternoon – $T_{outside}$ = 0°C

↓

$\alpha_{demoulding}$ = 62%

3. Thermal transformation of bulk layer

What can be improved and/or changed without altering the process too much?

M = Glass-polyester

S = Variable thickness

T = CFRP mould

E = Indoor/outdoor environment

E: Ambient temperature and airflow fluctuations. Temp = 0-30°C.

- Could add improved HVAC system to control temp/airflow/humidity
- Could insulate part from environment

T: Low thermal mass (heats up quickly), low diffusivity (may have hot/cold spots).

- Could change tooling material/geometry

S: Part thickness will influence amount of exothermic heat

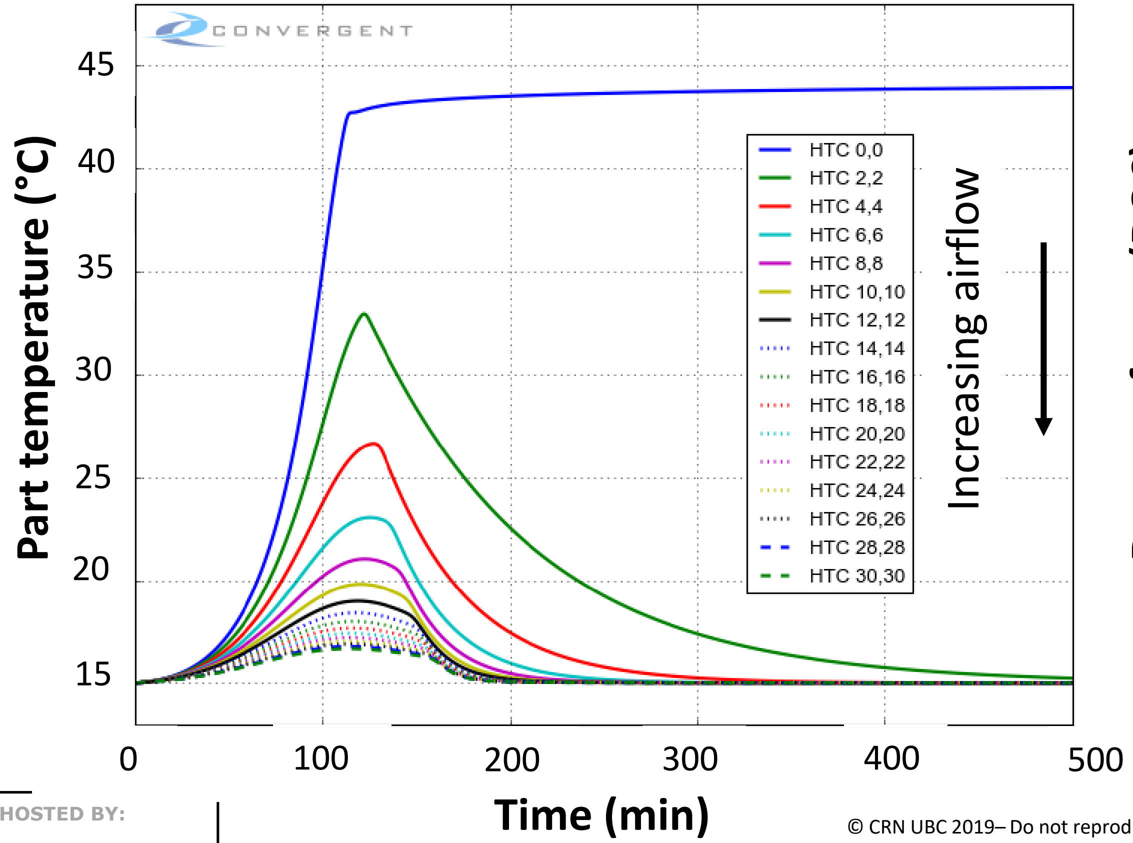
- Specifications to achieve same DOC for variety of thicknesses

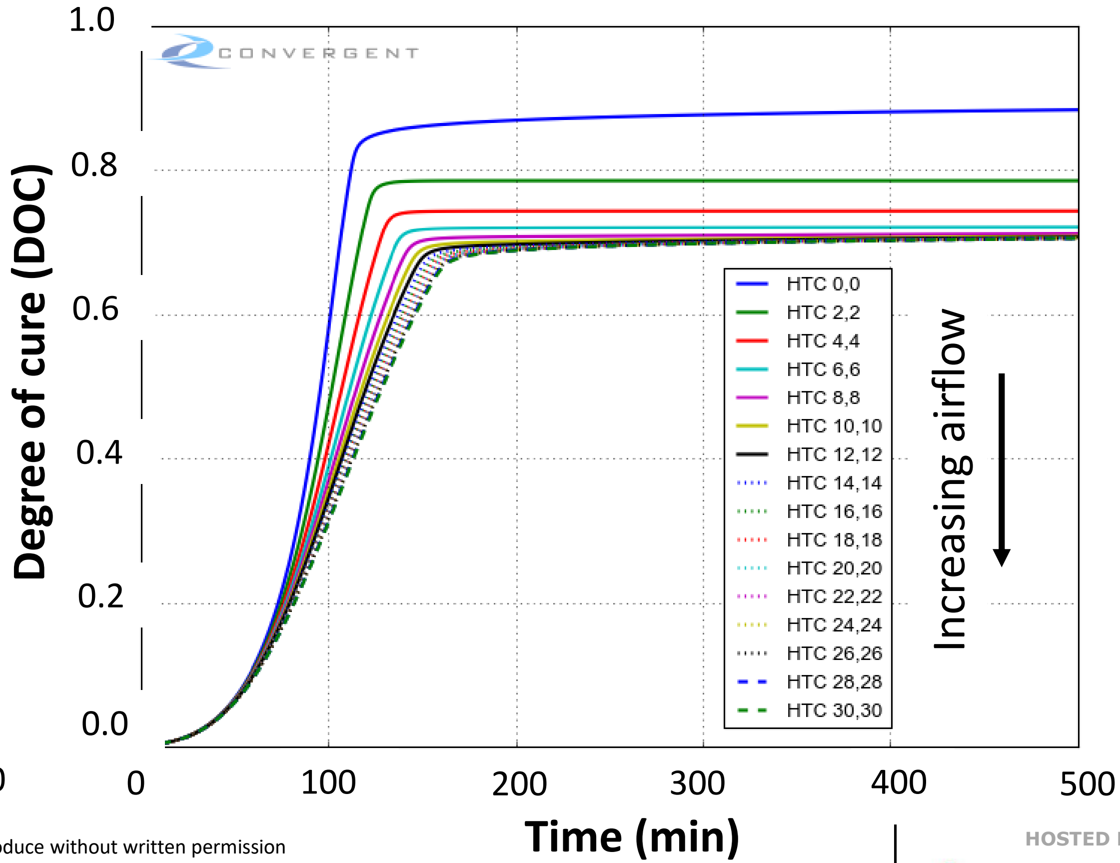
M: DOC is a function of time and temperature

- Investigate influence of processing conditions on DOC → Already discussed

E: Insulate part from environment

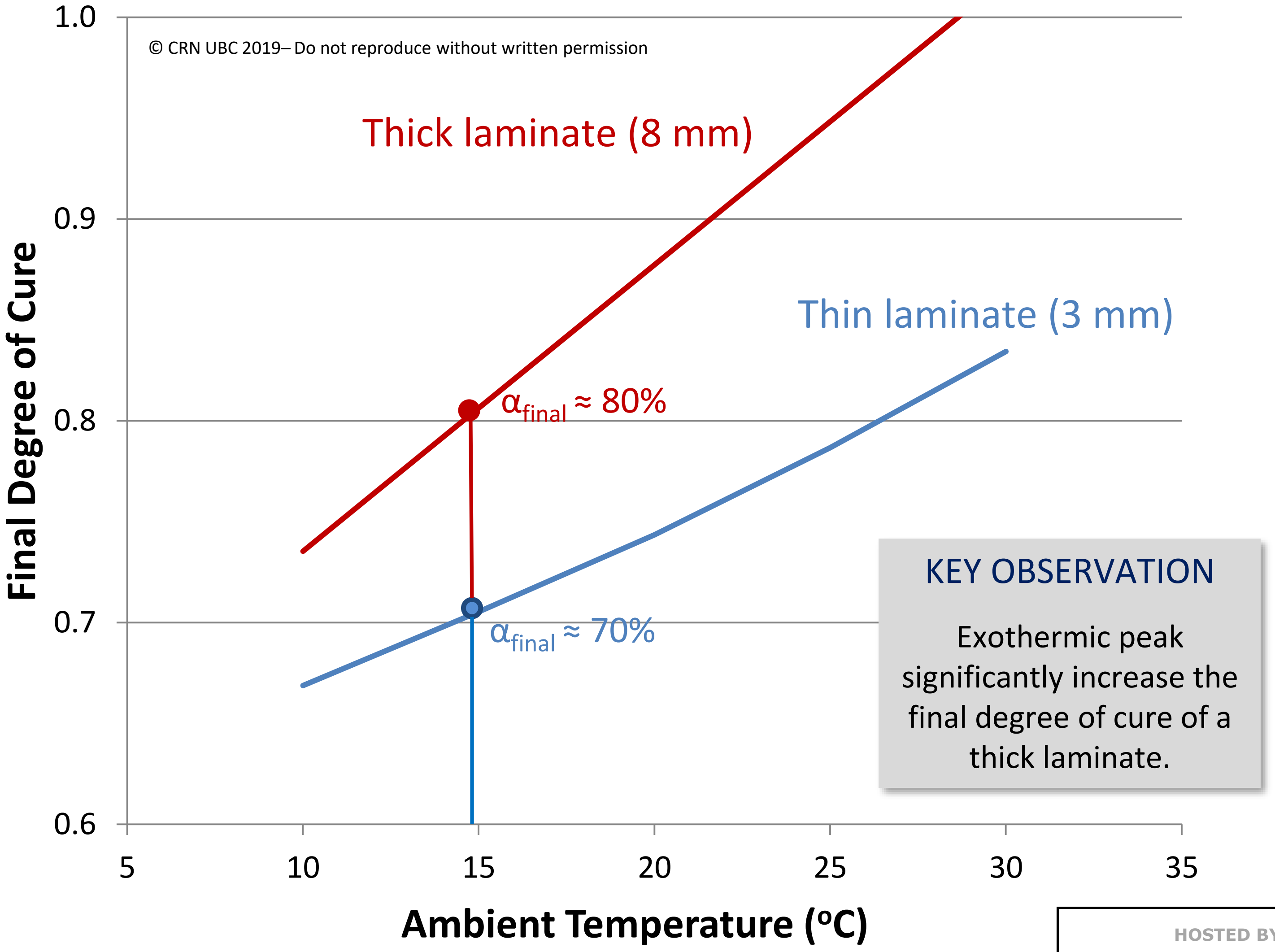
- Exothermic heat drives cure reaction.
  - Airflow acts to cool parts (in this case)





S: Variable part thickness on DOC

- Thinner part will achieve lower DOC under same conditions
- Mitigation strategies might include:
  - Raising ambient air temperature for thin parts
    - Cure outdoors in summer (or when temp is >25°C)
    - Implement a heater with a fan
    - Use heated a heat blanket
    - Use heated tooling
    - Use an oven
  - Insulating thin parts



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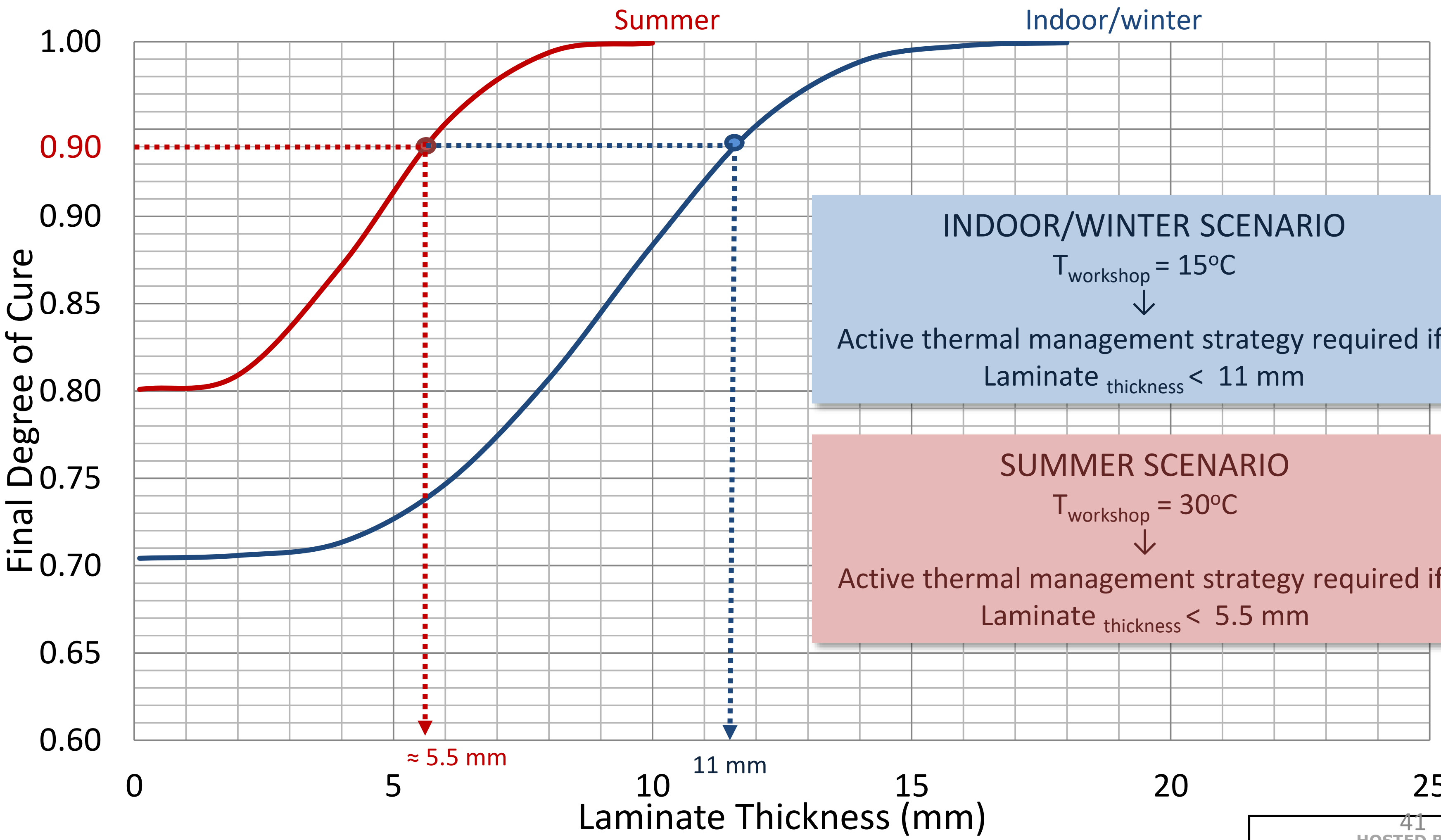
S: Specifications to achieve same DOC for different thicknesses

- Define cure specification

  $\alpha_{final} > 0.9$

Thermal management specifications:

- Laminates less than 11mm should be cured in temperatures above 15°C
- Laminates less than 5.5mm require temperatures greater than 30°C



INDOOR/WINTER SCENARIO

$T_{workshop} = 15^oC$

↓

Active thermal management strategy required if:

Laminate $_{thickness}$ < 11 mm

SUMMER SCENARIO

$T_{workshop} = 30^oC$

↓

Active thermal management strategy required if:

Laminate $_{thickness}$ < 5.5 mm

Summary – system approach

- Workflow was identified to be troubleshooting
- Objective was to improve quality without detriment to cost, rate, or the environment
- Problem cells were identified
  - Thermal transformation of gel coat
  - Thermal transformation and storage of composite
- MSTE system for each process step was identified
- Relevant parameters for M, S, T, and E were identified
- Mitigation strategies investigated

Summary of identified mitigation strategies

Gel coat (for this material):

- If curing at 15°C, gel coat should be allowed to cure for 55-90 mins before bulk layer is deposited
- DOC = 0.2 to 0.4

Bulk layer (for this material):

- Laminates less than 5.5mm should only be cured when air temps are above 30°C
- Laminates less than 11mm should only be cured when air temps are above 15°C
- Alternatively, insulation of the part can be done to reduce heat loss from wind or indoor airflow
- Cure parts in fully in a controlled system
  - Indoors with additional heat source and good HVAC
  - Oven

Companies were able to successfully implement a variety of these strategies to meet quality metrics with no hinderance to cost, rate, or environmental metrics

Lessons learned

- It is important to achieve a proper degree of cure
  - For thin parts (i.e. gel coat, thin bulk layer)
    - Controlling ambient air temperature is very important
    - Might consider insulating the part
  - For thick parts
    - Exotherm heat will help bring the part to temperature
    - Controlling air temperature to get the reaction started is still important
    - Must be weary of parts thermally degrading.

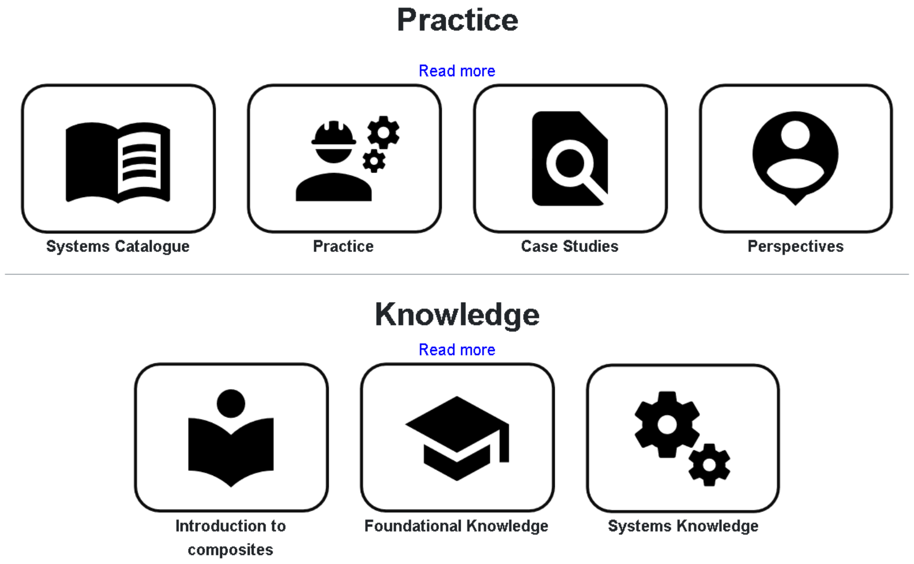
- Consider the interaction between the material, shape, tooling & consumables, and equipment

Exciting news

Coming soon

CKN KNOWLEDGE IN PRACTICE CENTRE

- Everything presented today will be included in an online format on the KPC!
- The KPC is a freely available online resource for composites engineers
- Focuses on practice, guided by foundational knowledge and a systems-based approach to thinking about composites manufacturing
- What this includes:
  - Individual documents describing the foundational and systems-based knowledge behind the case study presented today
  - The case study itself, plus others
  - Practice documents
  - Perspectives from composite experts
  - And much more
  - Additional content constantly being added
- Coming soon…



Thank you for joining us!

Keep an eye out for announcements on the next AIM events

Questions?

For more information on future dates and times visit:

compositeskn.org