VARTM PROCESS VARIABILITY STUDY

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Outline

- Objectives and Motivation
- Approach
- Theory
- Experimental set-up
  - ✦ Materials
  - ✦ Process
  - ✦ Cycle time
- Conclusions
- Future work

Objectives

Achieve a repeatable VARTM process by:

- **Identifying**
- **Understanding**
- **Evaluating**
- **Controlling**

the sources of process variations affecting the final part:

- Quality
- Dimensional tolerances
- Mechanical properties

While maintaining a low cost process for composite parts dedicated to high-performance applications:

- **Aerospace**
- **Naval applications**

Motivation

VARTM process: +/-

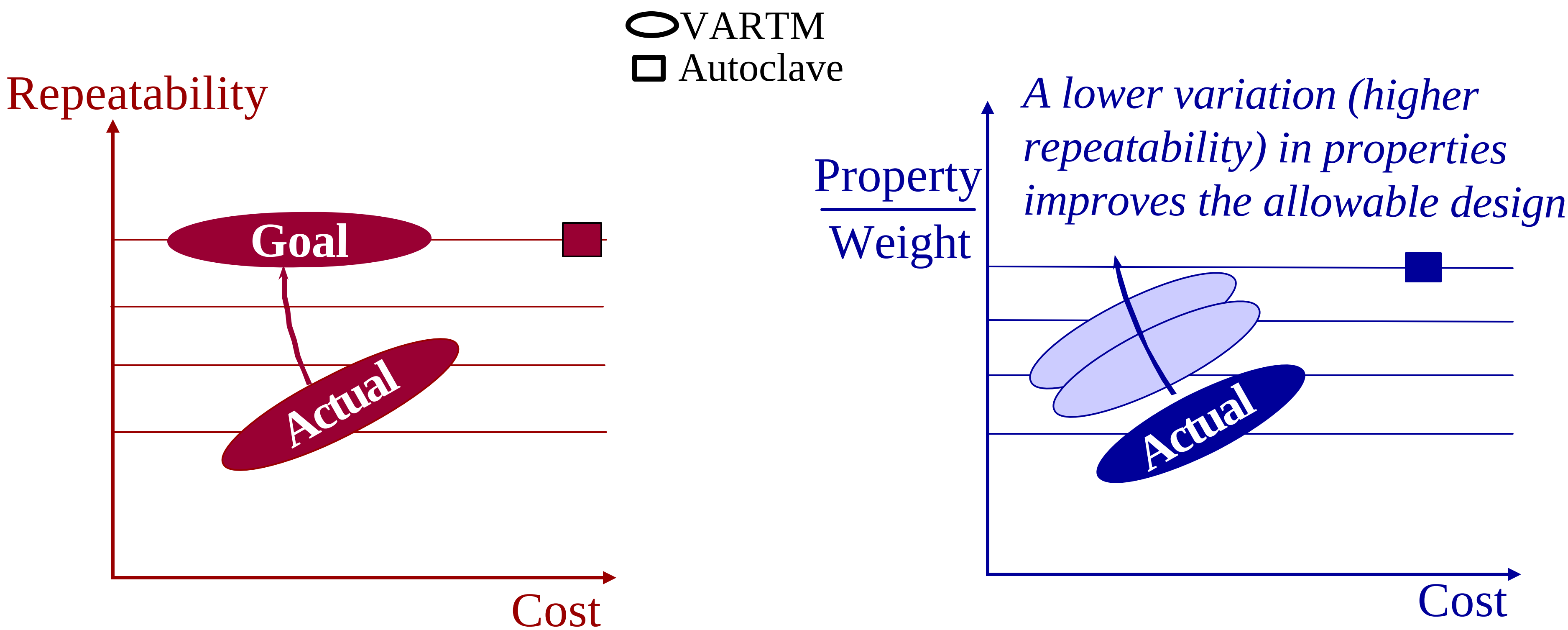
- **Main advantages: low cost, high fiber volume fraction, large scale parts**
- **Still some limitations**
  - High variability compared to autoclave process
    - From part to part
    - In the same part

Autoclave repeatability difficult to achieve with VARTM

Comparison VARTM/Autoclave:

		VARTM	Autoclave
Fiber volume fraction gradient	DVf	± 10%	± 1-3%
Thickness gradient	Dth_F	± 10%	± 1-3%

VARTM vs. Autoclave

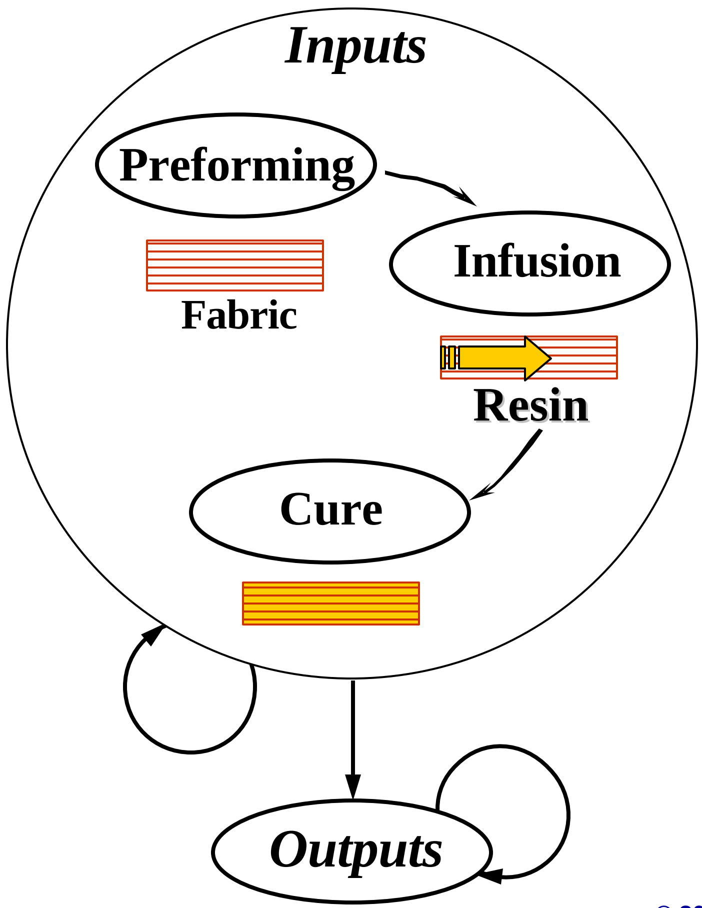


Following conditions have to be met to make VARTM viable for high-performance applications:

- **Process as repeatable as autoclave (reference)**
- **Slightly lower properties but for a much lower cost**

Sources of Variability

Materials as well as the Process have an impact on the repeatability



- **Inputs**
  - Incoming materials
  - Infusion parameters
  - Cure parameters
- **Outputs**
  - Quality of the part
  - Mechanical properties

Manual vs. Automated Set-Up

Current industry practice	Future industry practice: Variability identified		
Manual lay-up	Manual lay-up		Automated lay-up (laser cutting)
Manual infusion	Automated infusion	SMART Molding	Automated infusion
Manual control	Automated control		Automated control
NO Monitoring	**MONITORING** – SMARTMolding set-up		

Approach

- **Theory**

Identification of potential sources of variation → Evaluation of the different degrees of influence

- **Experimental**

Manufacture of a large number of panels

(Statistical) Analysis of data

- **Synthesis**

Model for prediction/optimization of the process variations

Actions to control the real sources of variations

Theory

1) Gather parameters influencing VARTM variations

Literature review

2) Screen the parameters

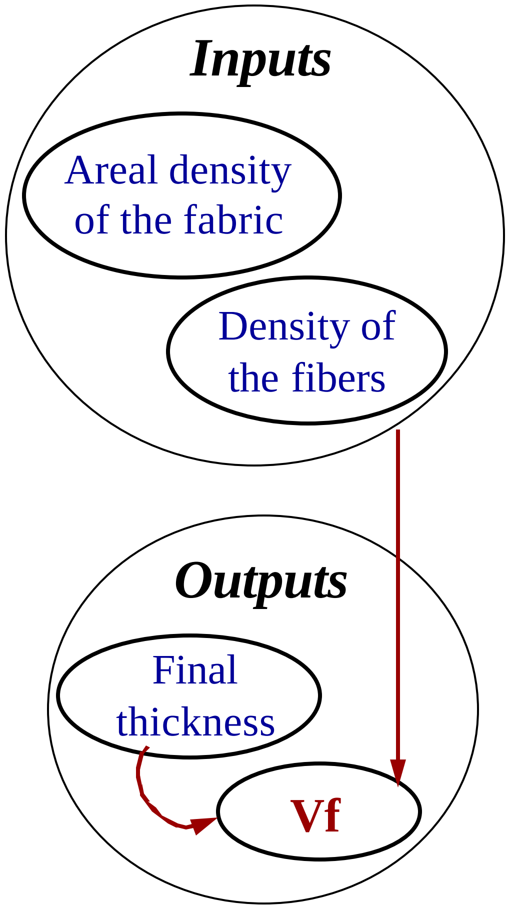
For each critical parameter

(Example: fiber volume fraction, V_f)

1) **Identify contributing parameters**
   - Areal density of the fabric
   - Density of the fibers
   - Final thickness of the part

$$V_f = \frac{n \times \rho_A}{th_f \times \rho_f}$$

2) **Evaluate their variations**
3) **Rank parameter contributions**



3) Example:

Rank **3**		Rank **2**		Rank **1**
$\left.\frac{\Delta V_f}{V_f}\right\|_{\Delta\rho_f} = -2.5\%$	<	$\left.\frac{\Delta V_f}{V_f}\right\|_{\Delta\rho_A} = 3.34\%$	<	$\left.\frac{\Delta V_f}{V_f}\right\|_{\Delta th_F} = -5\%$

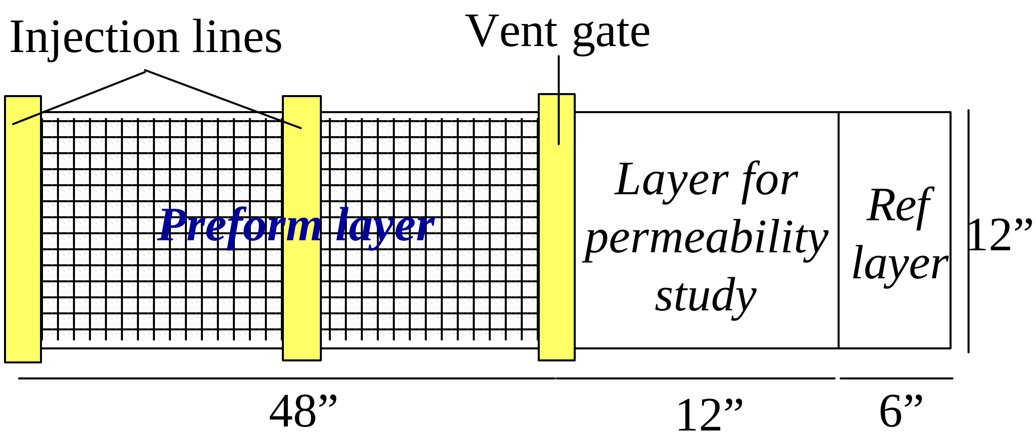
Experimental Set-Up

System

24 oz. Woven fabric E-glass
Dow Derakane Momentum 411-100

Materials

Fabric : Weight, Size, Areal density, Permeability, Porosity
Resin : Viscosity, Mix-ratio
Consumables : Weight



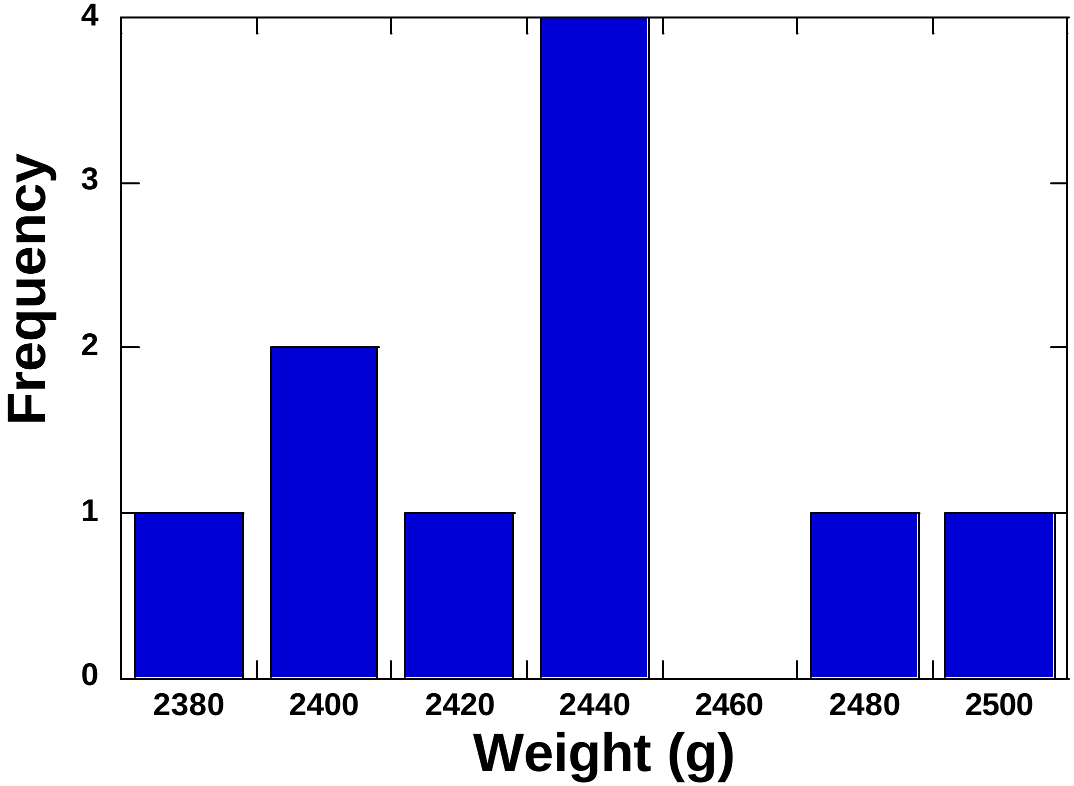
SMARTMolding processing

Operator : Accuracy, Cycle time
Processing variability : Vacuum leak, Infusion time, Gel time

Materials: Fabric Weight
(source of variation: preform)

Manual cutting

Fabric weight = 2426 g ± 1.4%



Contributing parameters: **Operator**
Areal density

Future work:

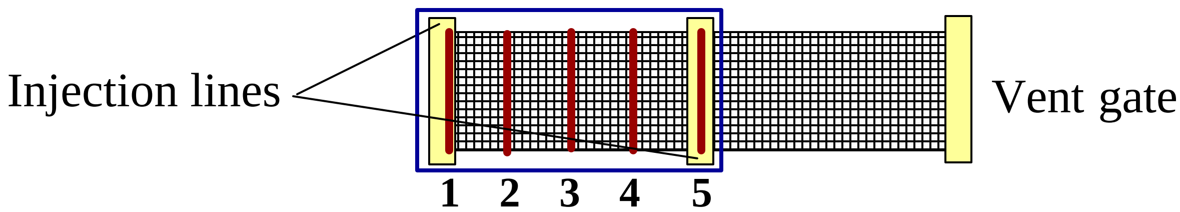
Measurement of

-*Areal weight, Porosity (affect directly V_f)*

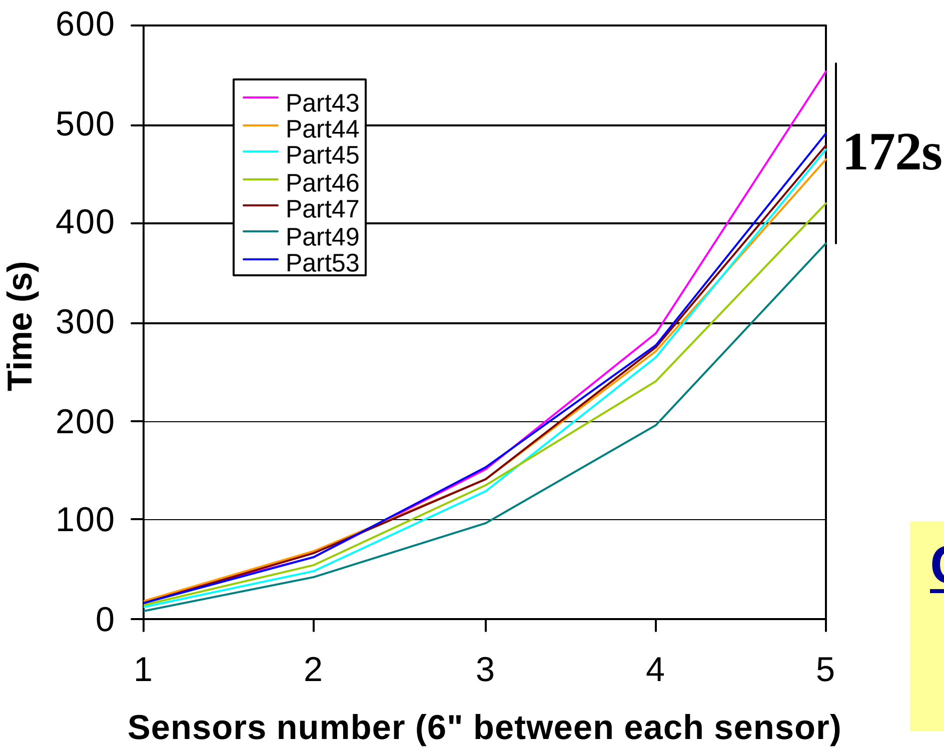
-Permeability

Process: Arrival Time
(source of variation: infusion)

Infusion – Focus on the 1st part of the injection:



The variations are almost constant with flow distance.

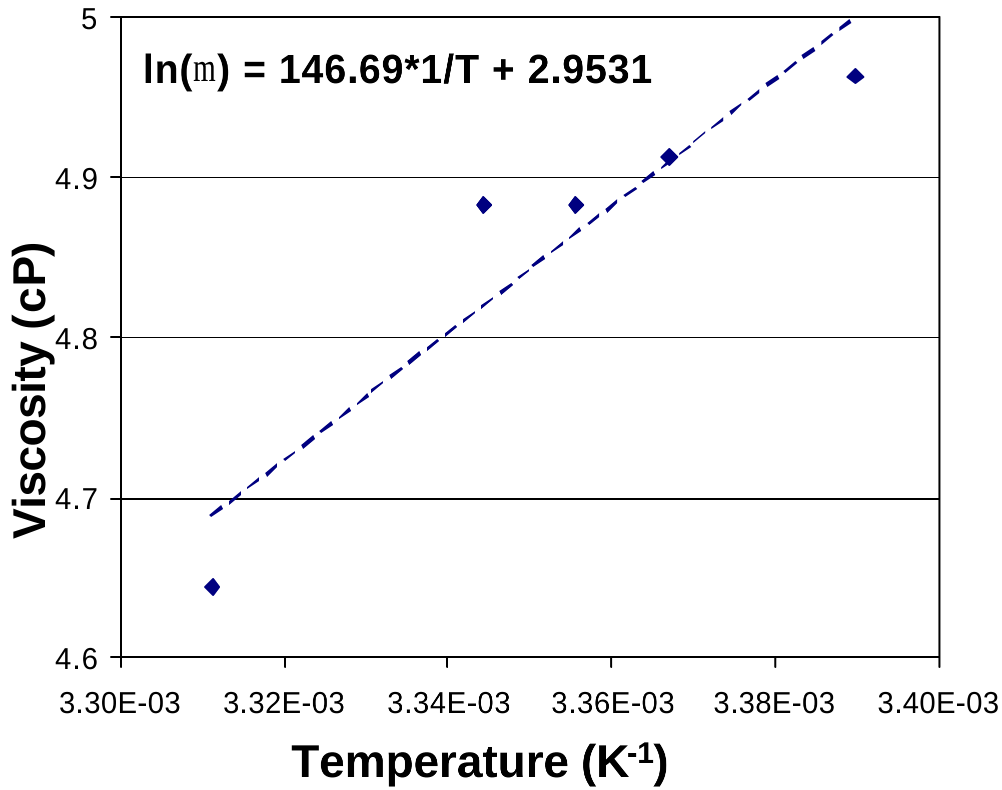


Sensor number	Variability of the time (%)
Sensors 1	18.8
Sensors 2	17.1
Sensors 3	14.8
Sensors 4	14.4
Sensors 5	14.6

Contributing parameters: **Viscosity**
Permeability
Porosity

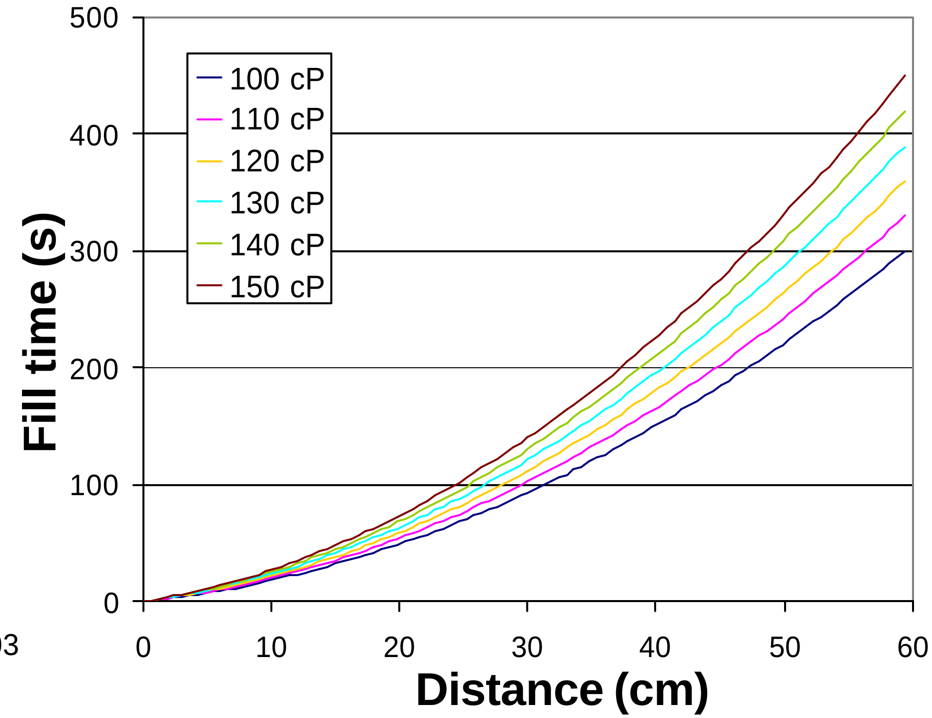
Materials: Resin Viscosity
(source of variation: infusion)

Viscosity = 129.4 cP ± 11.5%



Fill time at 60cm = 375s ± 14.9%

(modelisation)

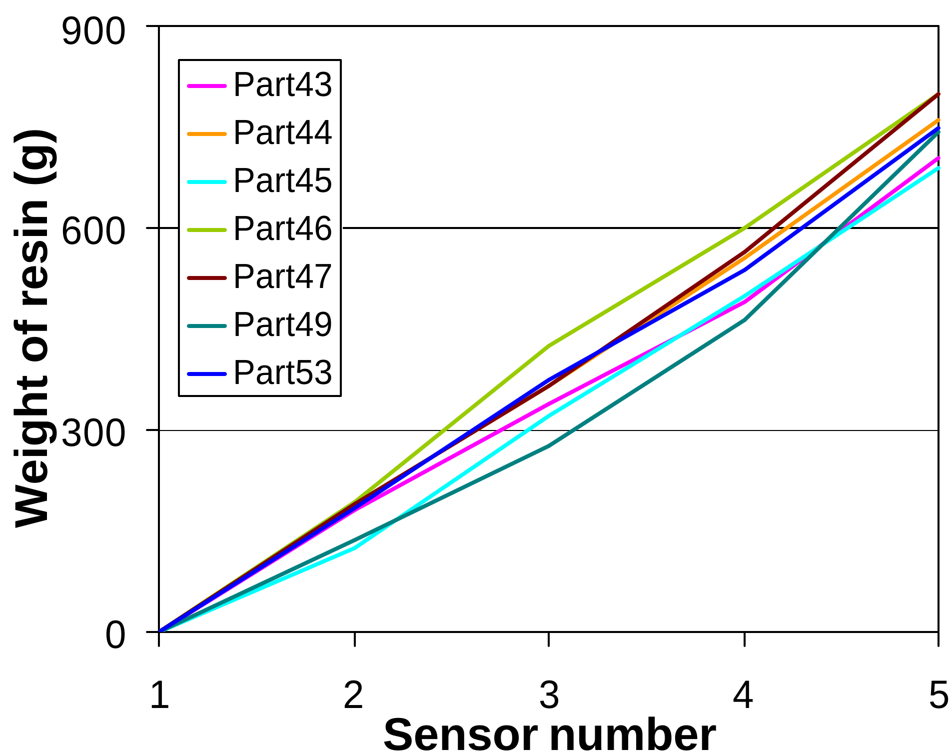


Contributing parameters: Temperature

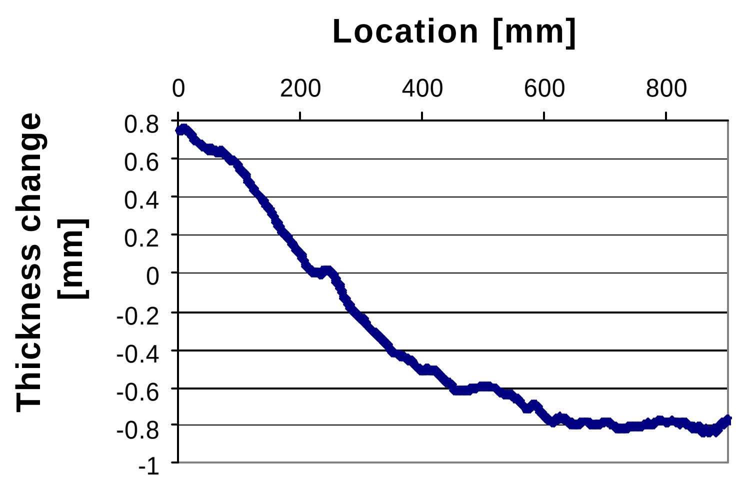
Mix-ratio

Process: Resin Volume
(source of variation: infusion)

Injected resin vs. Sensor distance



Sensor number	Variability of the amount of resin (%)
Sensors 2	16.8
Sensors 3	13.4
Sensors 4	9
Sensors 5	5.6



⇒Variability is distance sensitive

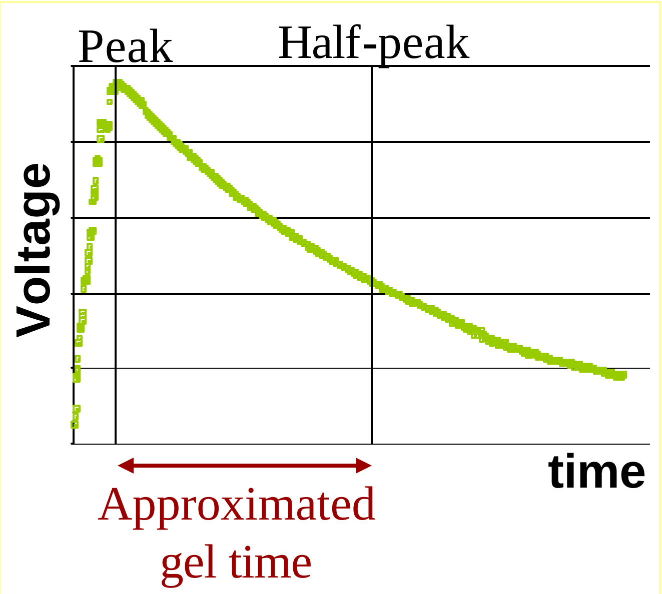
⇒Fiber volume fraction: V_f = f(part size)

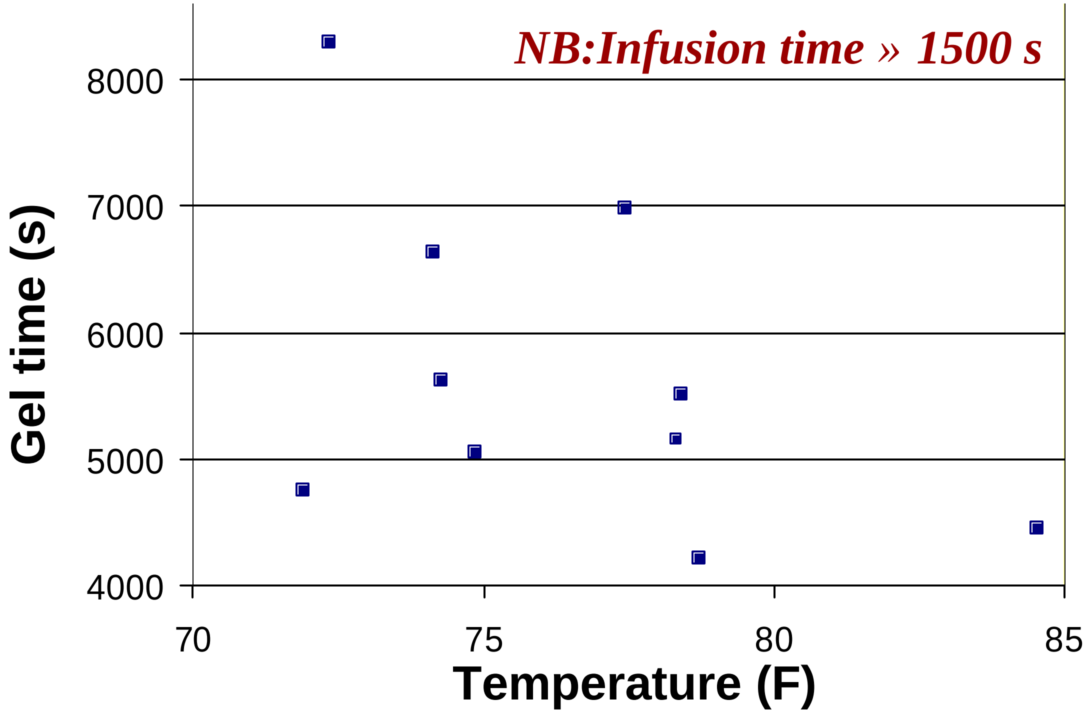
⇒Other factors can include permeability (flow shape) of DM and preform

Process: Cure

Gel time: 1st approximation Þ half-peak time

Gel time = 1:46 ± 21.7%





Contributing parameters:

- **Ambient temperature**
- **Exothermic reaction**
- **Mix-ratios**

Future work will include:

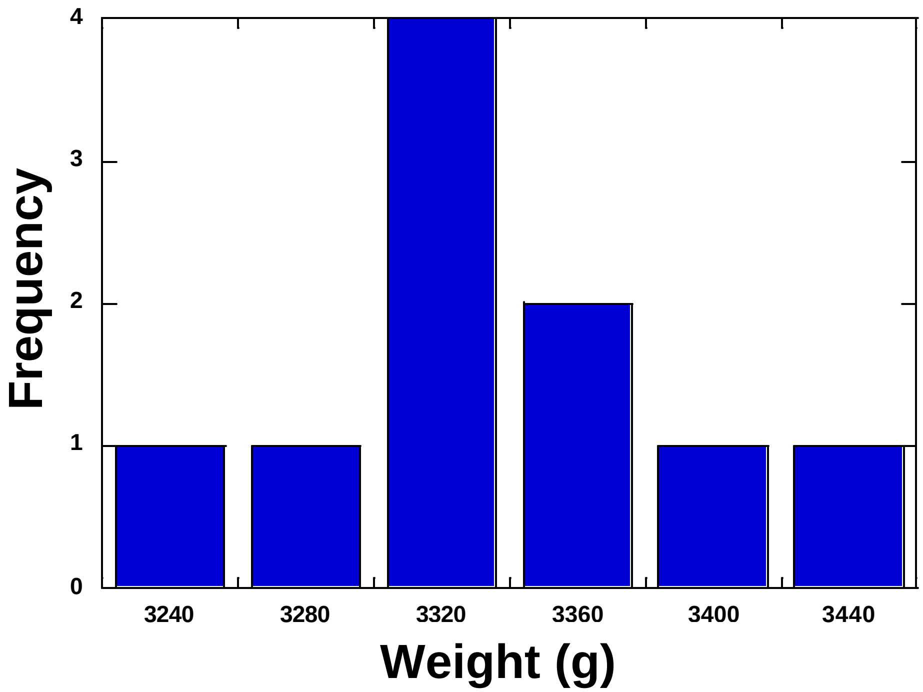
-K. M. England & M. B. Dorairaj prediction of gel time

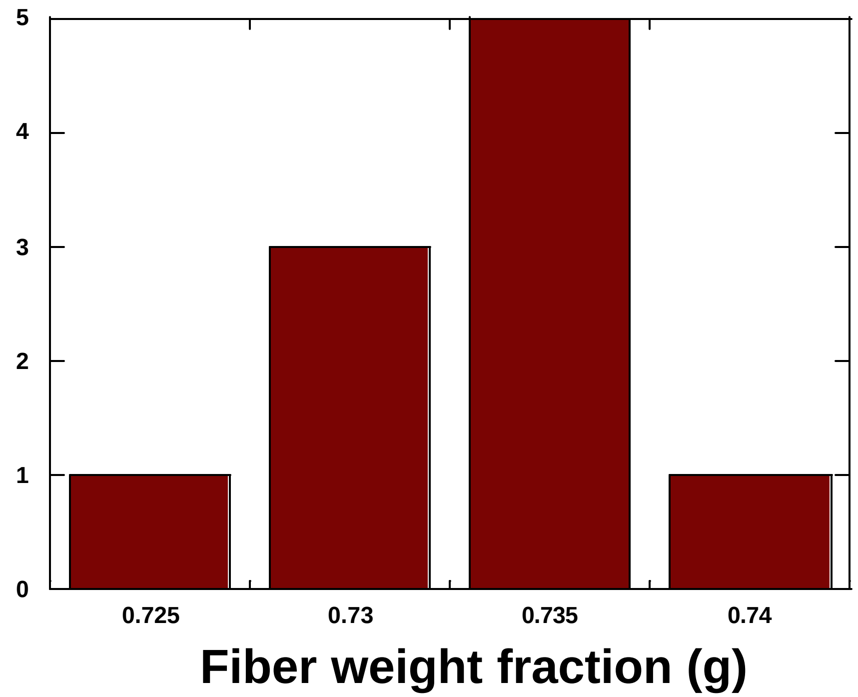
-Monitor and control of mix-ratios

Process: Final Part

Weight (final part) = 3320 g ± 1.7%

Fiber weight fraction = 73% ± 0.55%





Contributing parameters:

Initial fabric weight

Final thickness

Future work: Quality of the part (Void content, Fiber volume fraction), Mechanical properties.

Cycle Time Variability

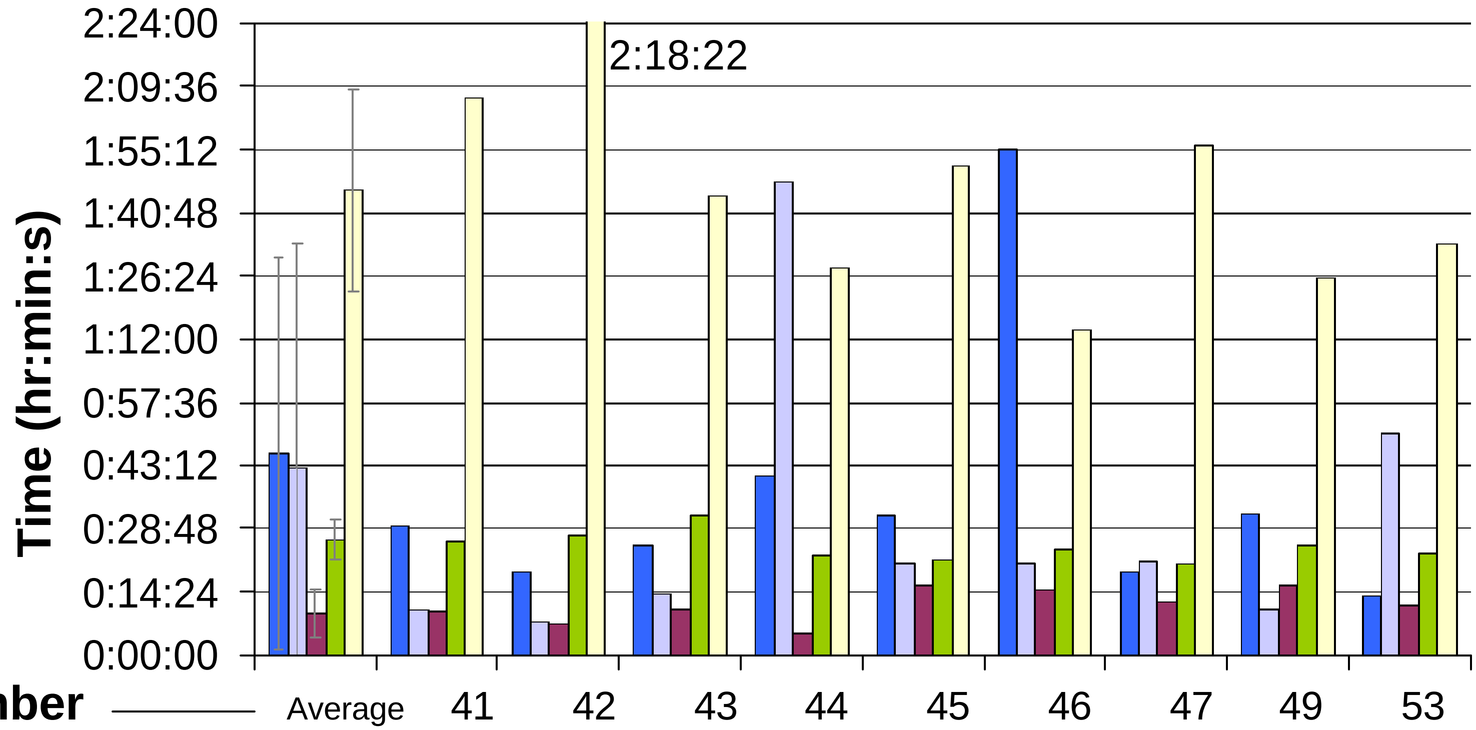
	VARIATIONS	
Operator	Mold prep + lay-up	: 0:46:02 ± 97%
	Bagging	: 0:42:35 ± 120%
	Vacuum check	: 0:09:30 ± 57%
Automated	Infusion	: 0:26:23 ± 18%
	Gel time	: 1:46:04 ± 22%

SOLUTIONS

"Kitting of material is key"

"Reusable bagging"

"Reusable bagging"



Conclusions

- Initiation of the first set in characterizing VARTM variations, Part-to-part only.
- Development of an experimental set-up to study incoming materials
- Identification of a first set of variations
  - Among the inputs
    - Materials
      - Fabric (weight)
      - Resin (viscosity)
    - Process' parameters
      - Injection (time to reach the sensors, amount of injected resin)
      - Cure cycle (gel time)

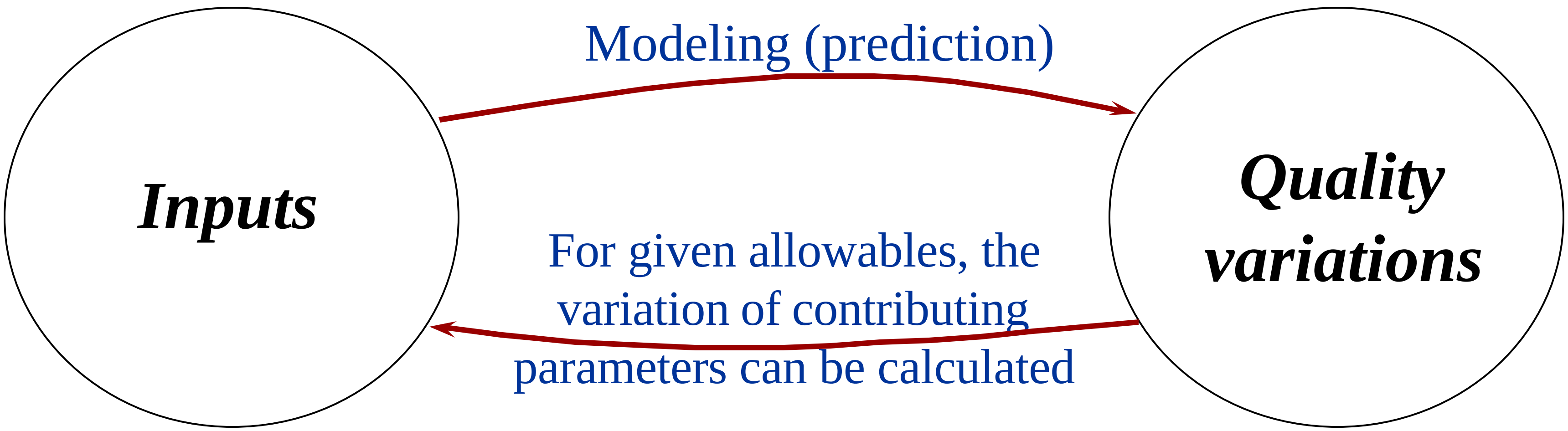
Current and Future Work (1/2)

- **Include:**
  - **Distribution media contribution to the variability of the process**
  - **Determine the variations of:**
    - Permeability
    - Porosity
    - Areal density
  - **Measure:**
    - Void content
    - Fiber volume fraction
    - Mechanical properties
  - **Create larger experimental data set for meaningful statistical results**
- **Variability increases with complexity of the part**
  - **Manufacture of panels with more complicated shapes (stiffener, 3D)**
- **Measure "in-part" variations**
- **Show benefits of automation**

Current and Future Work (2/2)

Long term objectives

- Create interaction between the quality of the part and the variations of the inputs



- Other materials
  - Carbon fibers
  - High-temperature resins

Description of the Parameters

Exhaustive list

✦ Preform

df	Diameter of the fibers
ρ_f	Density of the fibers
R_{tow}	Radius of the tows
S_{tow}	Saturation of the tows
Vf_{tow}	Fiber volume fraction of the fiber tows
K_{tow}	Permeability of the fiber tows
ρ_A	Areal density of the fabric
ϕ	Porosity of the fabric
K	Permeability
Cp	Compressibility
C	Compaction
th_i	Thickness of the final preform
Vf_{PW}	Fiber volume fraction - Wet fibers
Vf_{PD}	Fiber volume fraction - Dry fibers
n_{debulk}	Number of debulking cycles
P_{debulk}	Pression of the debulking cycles
Binder	Presence of binder

✦ Resin

μ_R	Viscosity of the resin
Er	Young's modulus of the resin
θ	Contact angle
P_{deg}	Degassing pressure
t_{deg}	Degassing time
Tg	Glass transition temperature
	Cure kinetics

✦ Infusion

K_{DM}	Permeability of the DM
V	Vacuum pressure
Q	Flow rate
$t_{infusion}$	Infusion time
tgel	Gel time
Tgel	Gel temperature
xv,yv	Vent location

✦ Resulting part

Vf_F	Final fiber volume fraction
Vv_F	Final void content
th_F	Final thickness
TS_F	Tensile strength
CS_F	Compression strength
$OHCS_F$	Open hole compression strength
σ_{fsF}	Flexural strength
ILLS	Interlaminar shear strength
Kc	Toughness
E_F	Young's modulus