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 <u>low cost</u> process for composite parts dedicated to high-performance applications:

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

Motivation

VARTM process: +/-

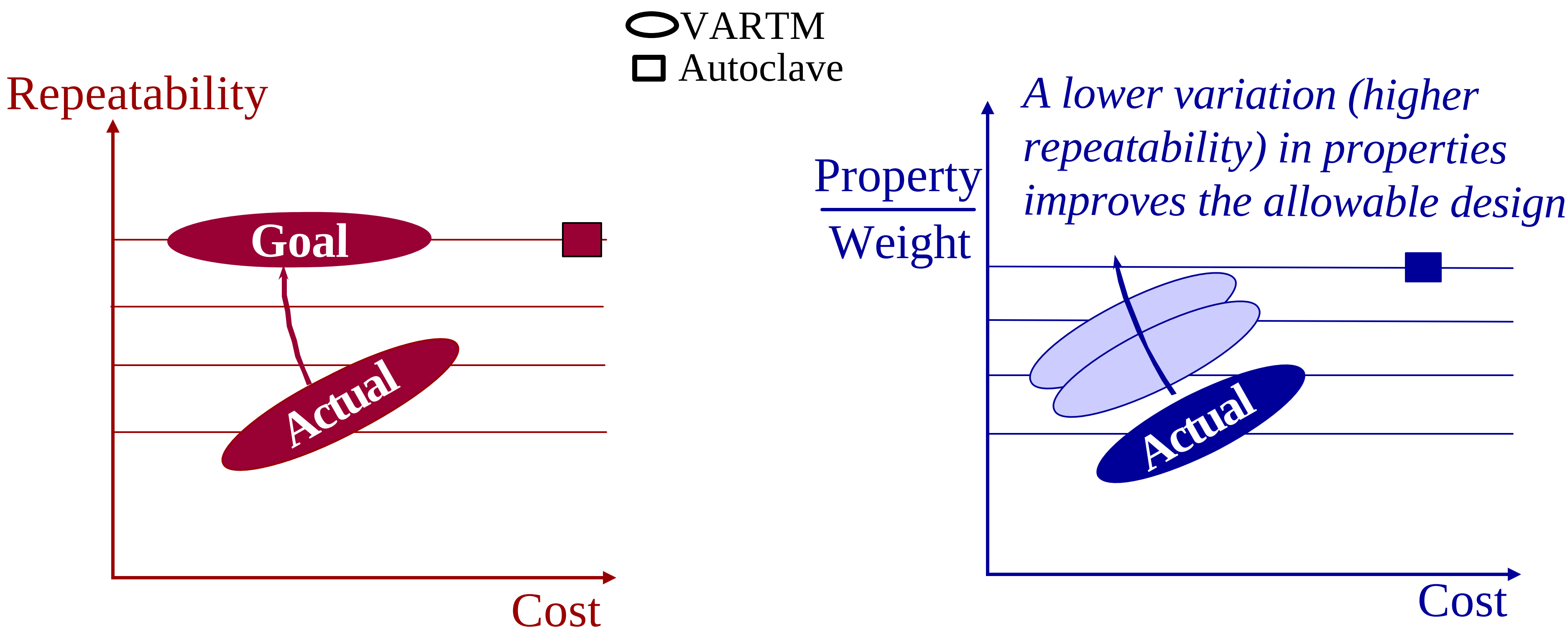
- **Main advantages: low cost, high fiber volume fraction, large scale parts**
- **Still some limitations**
  - High variability compared to autoclave process
    - From part to part
    - In the same part

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

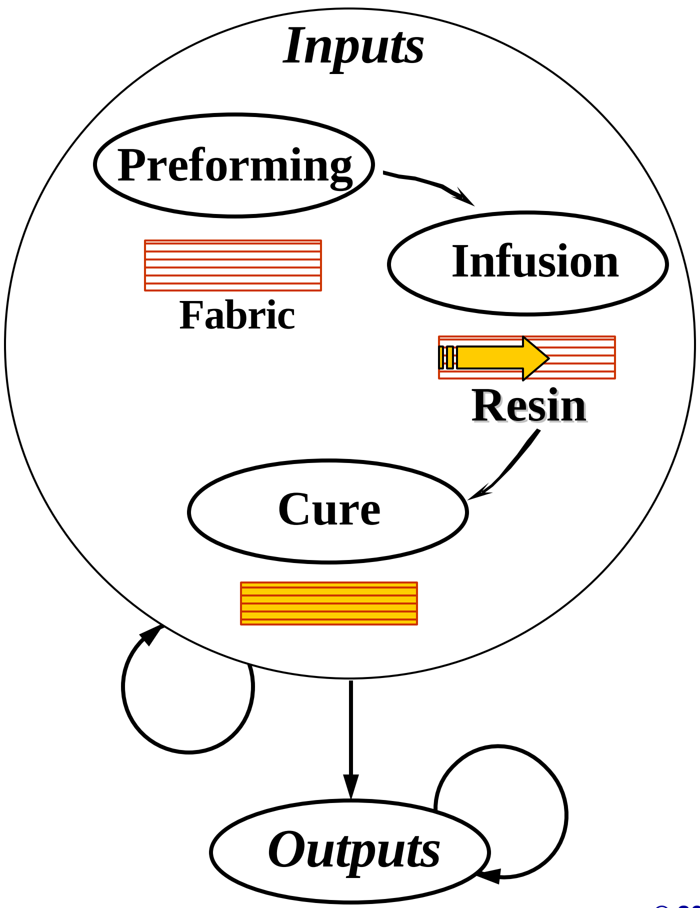


Following conditions have to be met to make VARTM viable for high-performance applications:

- **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

Manual lay-up

Manual infusion

Manual control

NO Monitoring

Future industry practice: Variability identified

Manual lay-up

Automated infusion

Automated control

SMART Molding

Automated lay-up (laser cutting)

Automated infusion

Automated control

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

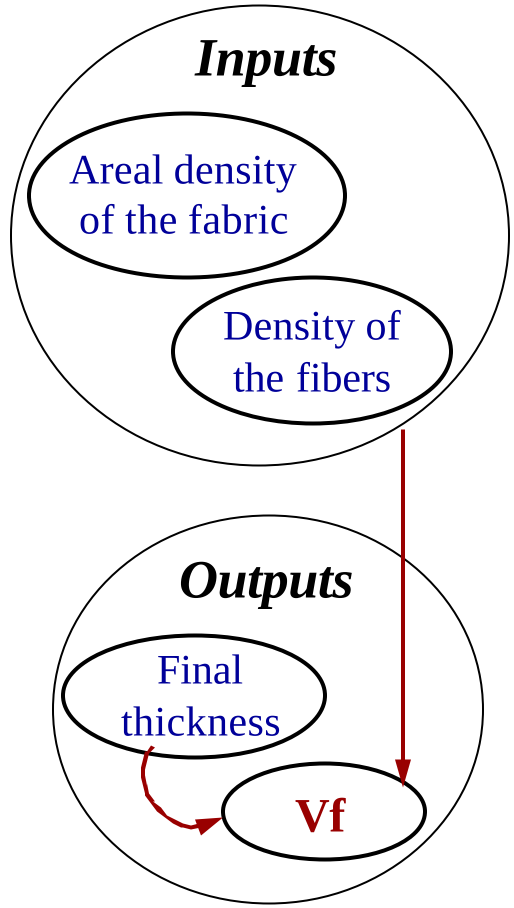
For each critical parameter

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

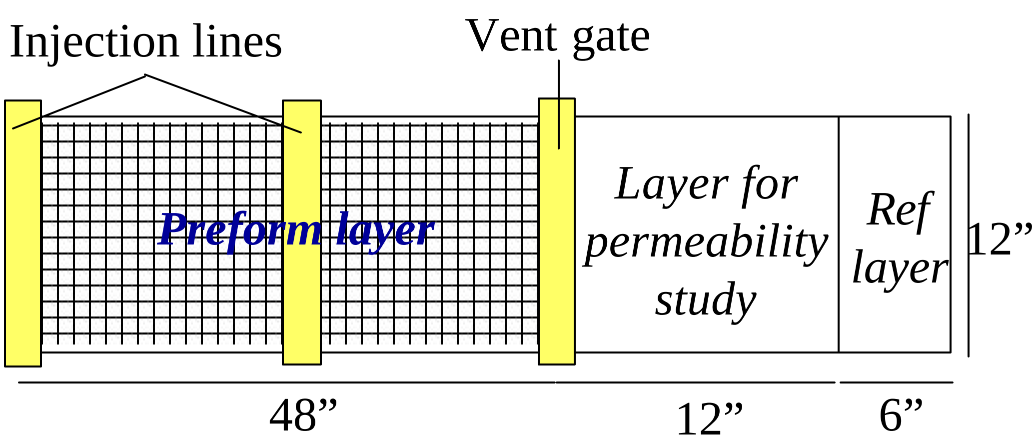
Experimental Set-Up

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



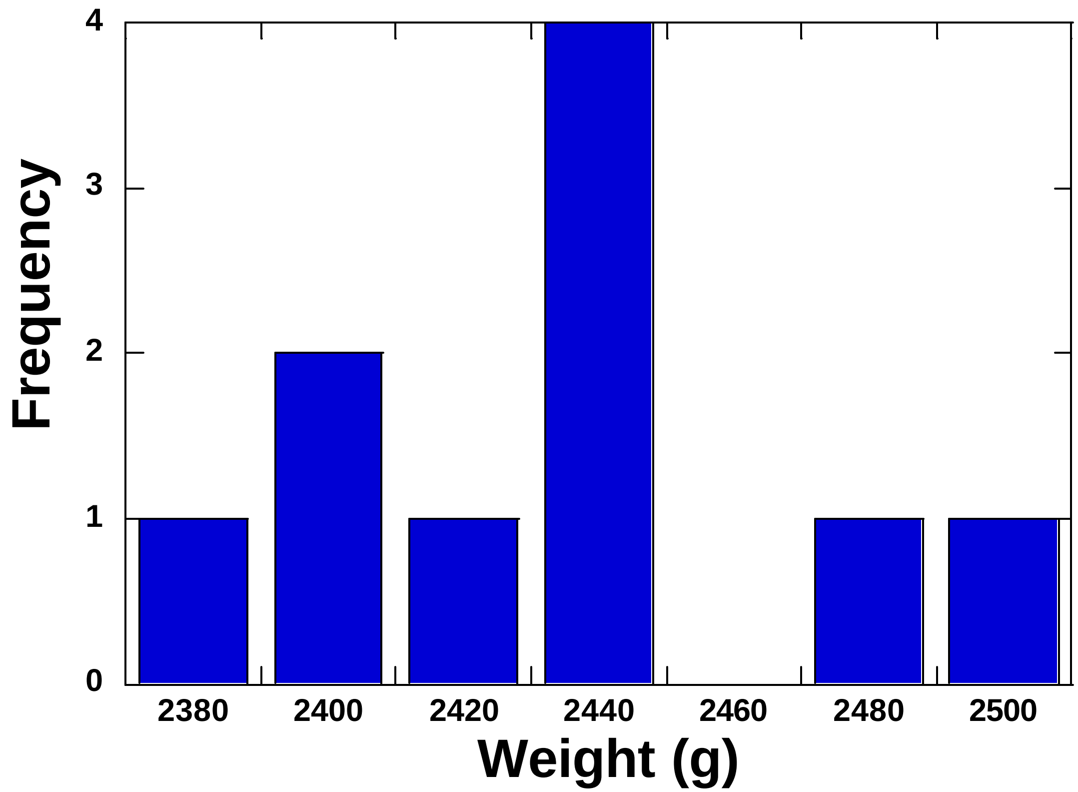
SMARTMolding processing

- **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:

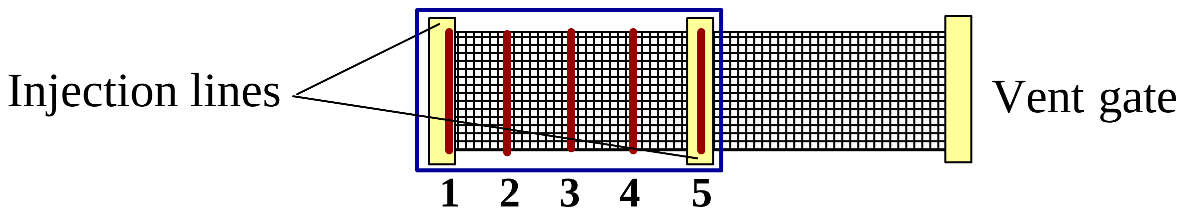
Measurement of

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

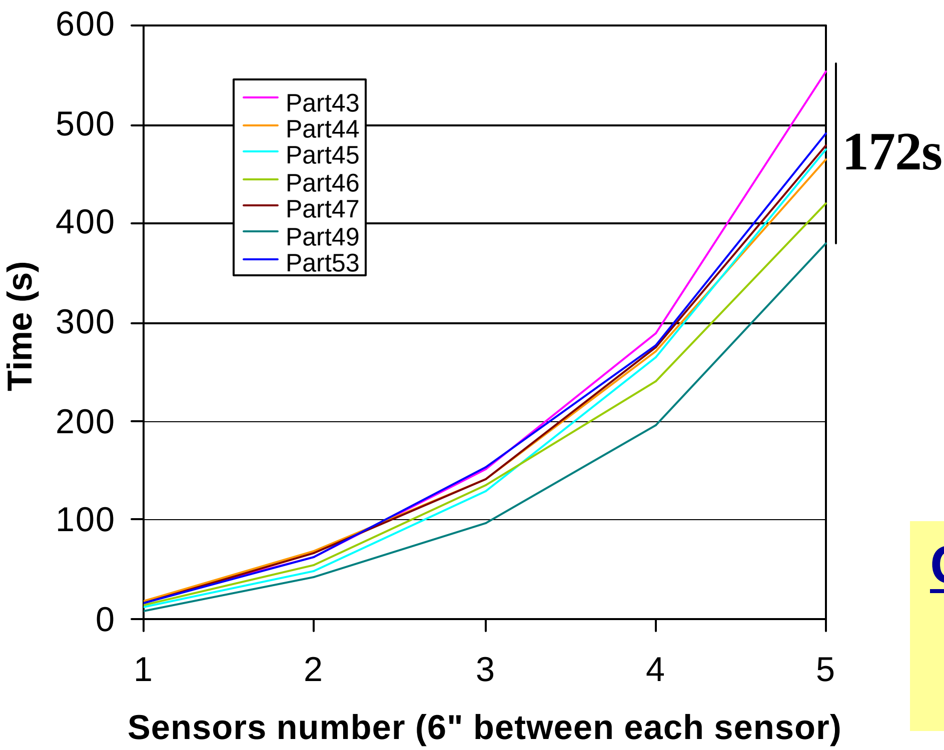
-Permeability

Process: Arrival Time
(source of variation: infusion)

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



The variations are almost constant with flow distance.

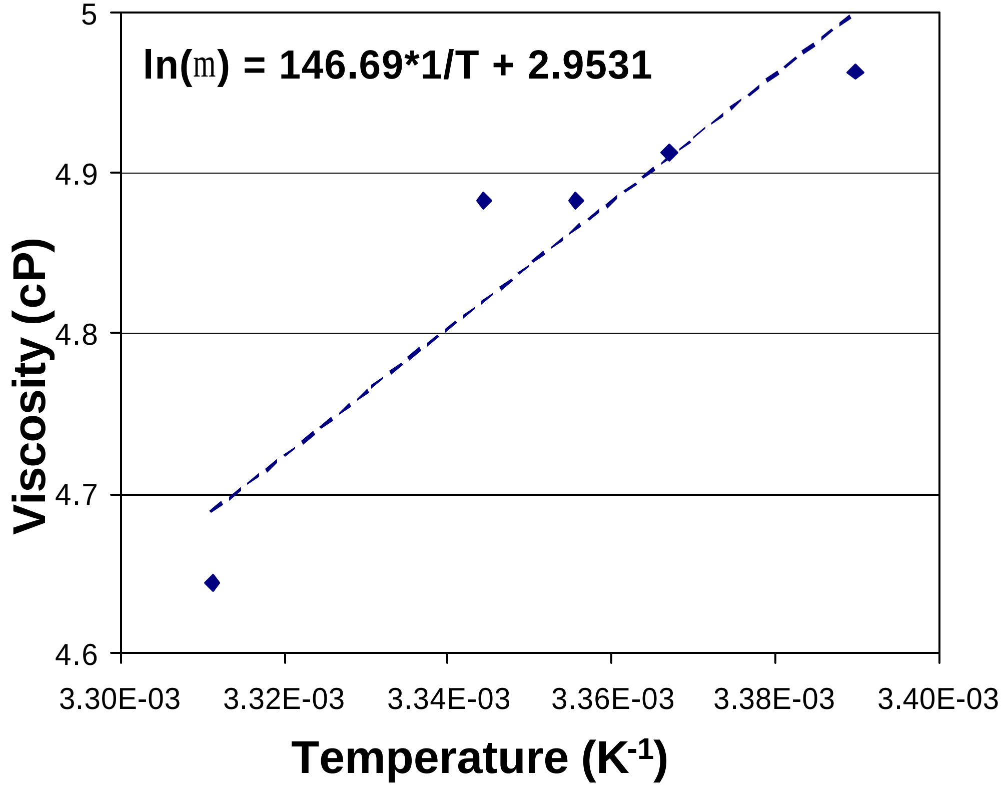


Sensor number	Variability of the time (%)
Sensors 1	18.8
Sensors 2	17.1
Sensors 3	14.8
Sensors 4	14.4
Sensors 5	14.6

Contributing parameters: Viscosity
Permeability
Porosity

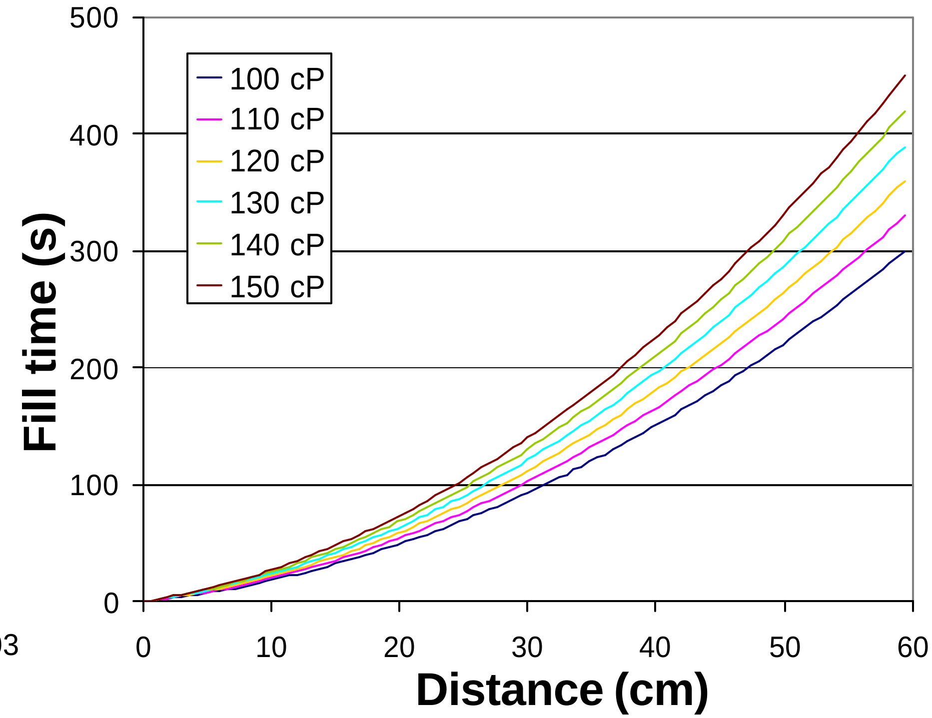
Materials: Resin Viscosity
(source of variation: infusion)

Viscosity = 129.4 cP ± 11.5%



Fill time at 60cm = 375s ± 14.9%

(modelisation)

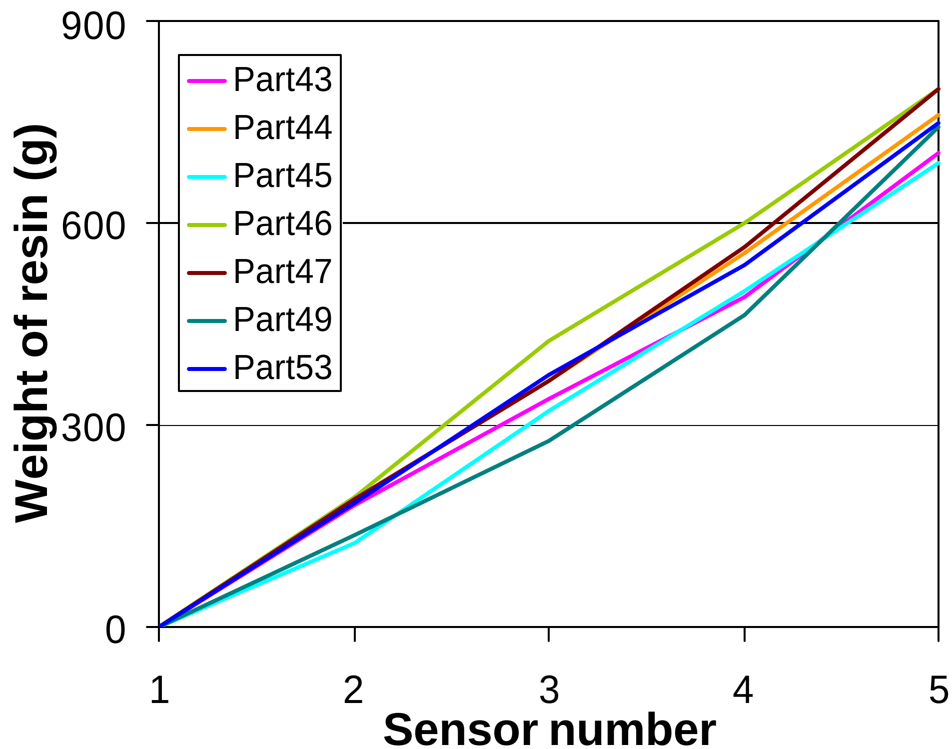


Contributing parameters: **Temperature**

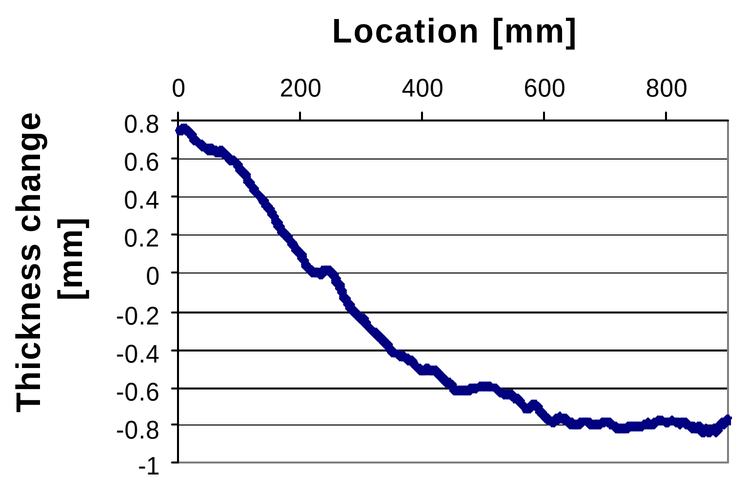
Mix-ratio

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

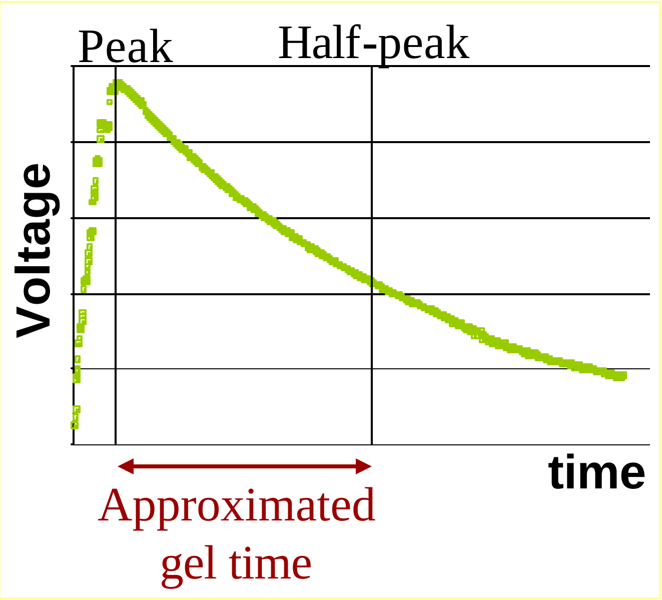
⇒Fiber volume fraction: V_f = f(part size)

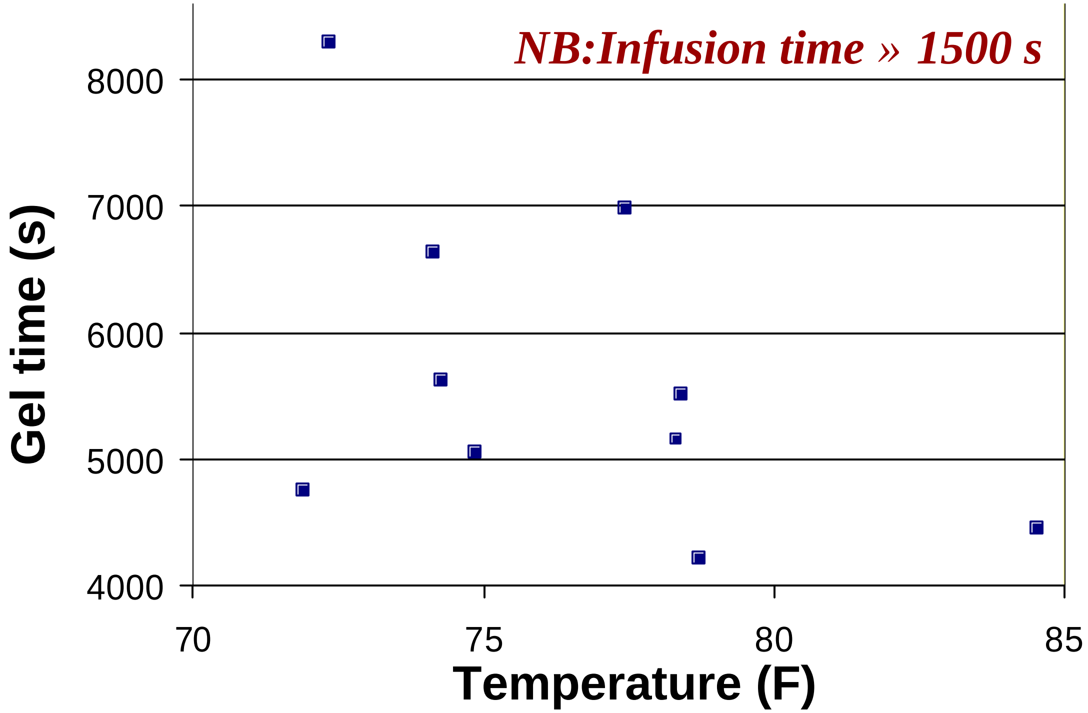
⇒Other factors can include permeability (flow shape) of DM and preform

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:

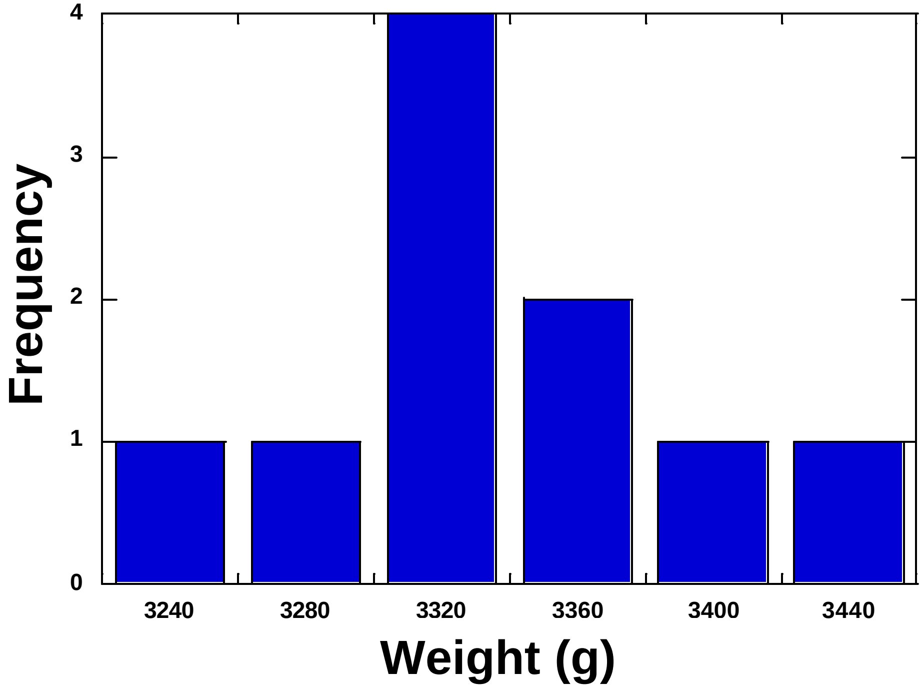
-K. M. England & M. B. Dorairaj prediction of gel time

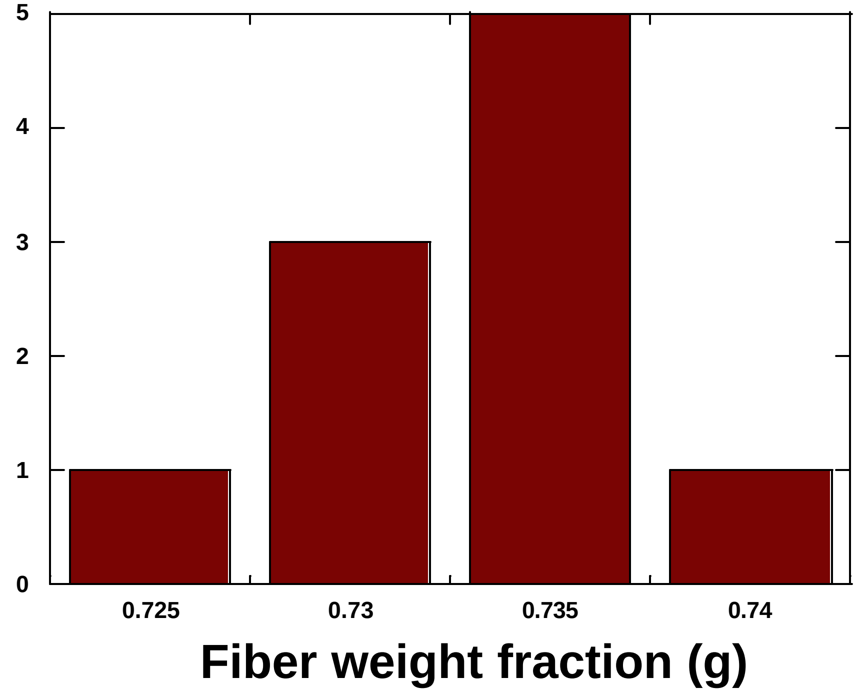
-Monitor and control of mix-ratios

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

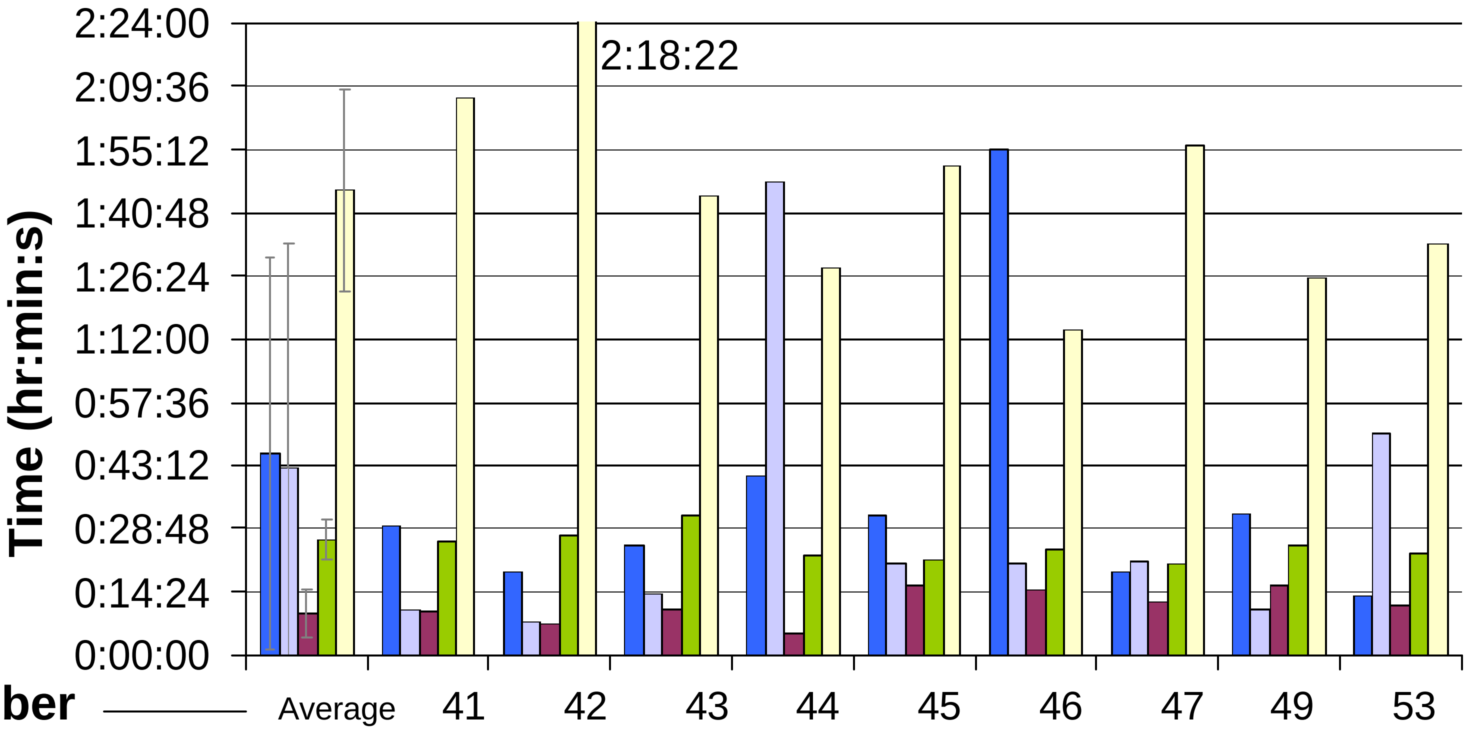
	VARIATIONS	
Operator	Mold prep + lay-up	: 0:46:02 ± 97%
	Bagging	: 0:42:35 ± 120%
	Vacuum check	: 0:09:30 ± 57%
Automated	Infusion	: 0:26:23 ± 18%
	Gel time	: 1:46:04 ± 22%

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)

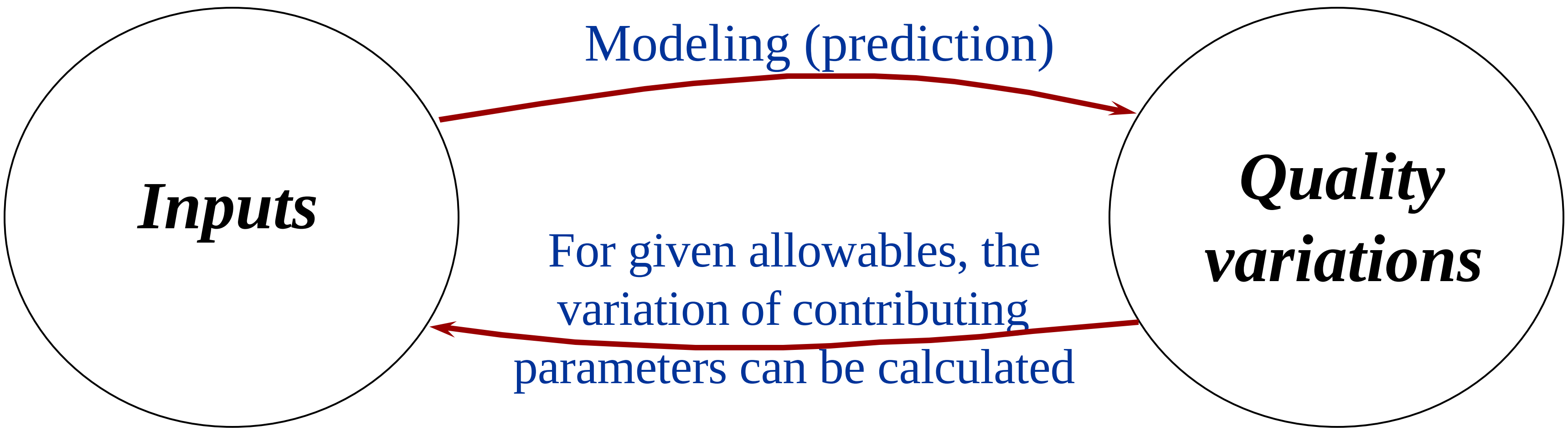
Current and Future Work (1/2)

- 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