Reimagining Aerospace Composites Manufacturing in an Industry 4.0 World

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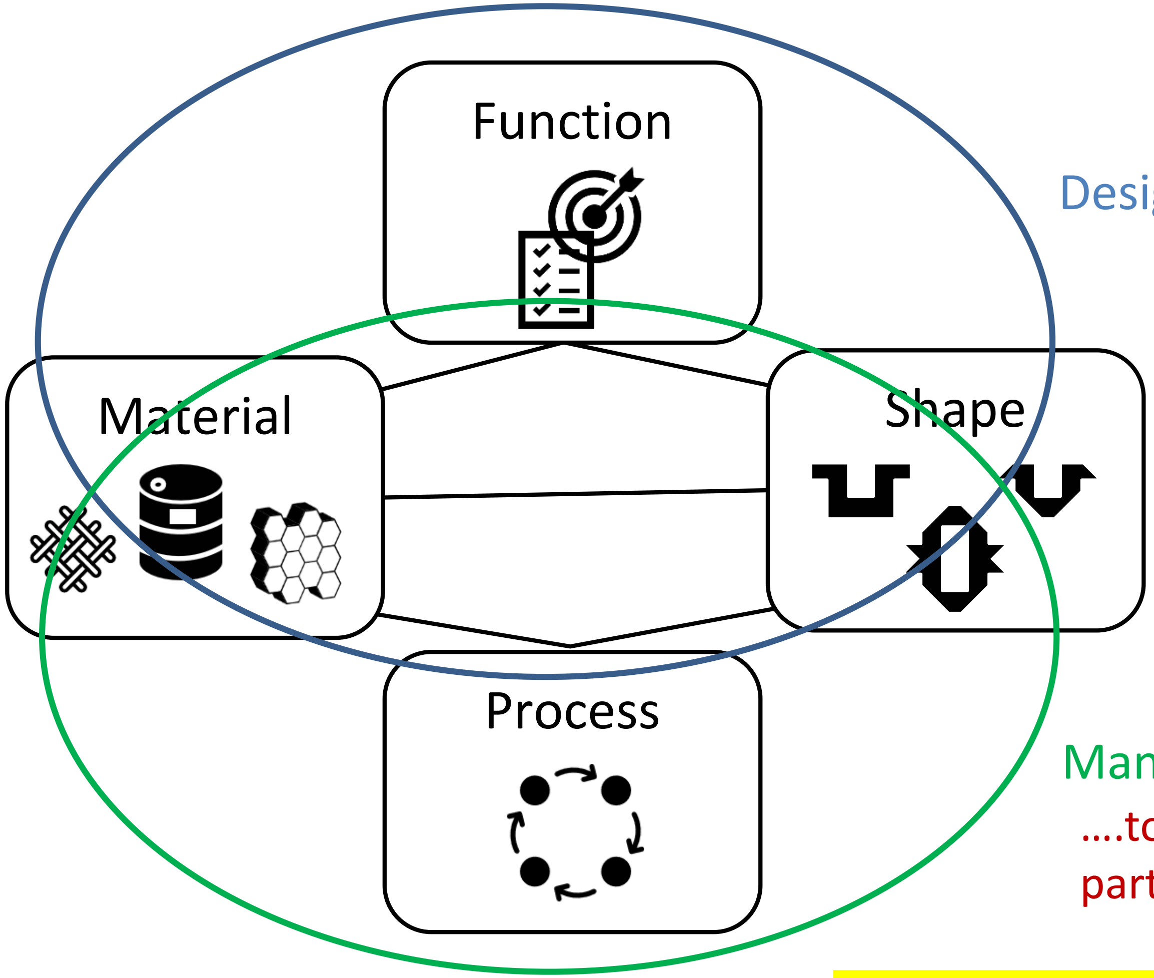
Selecting Materials and Processes



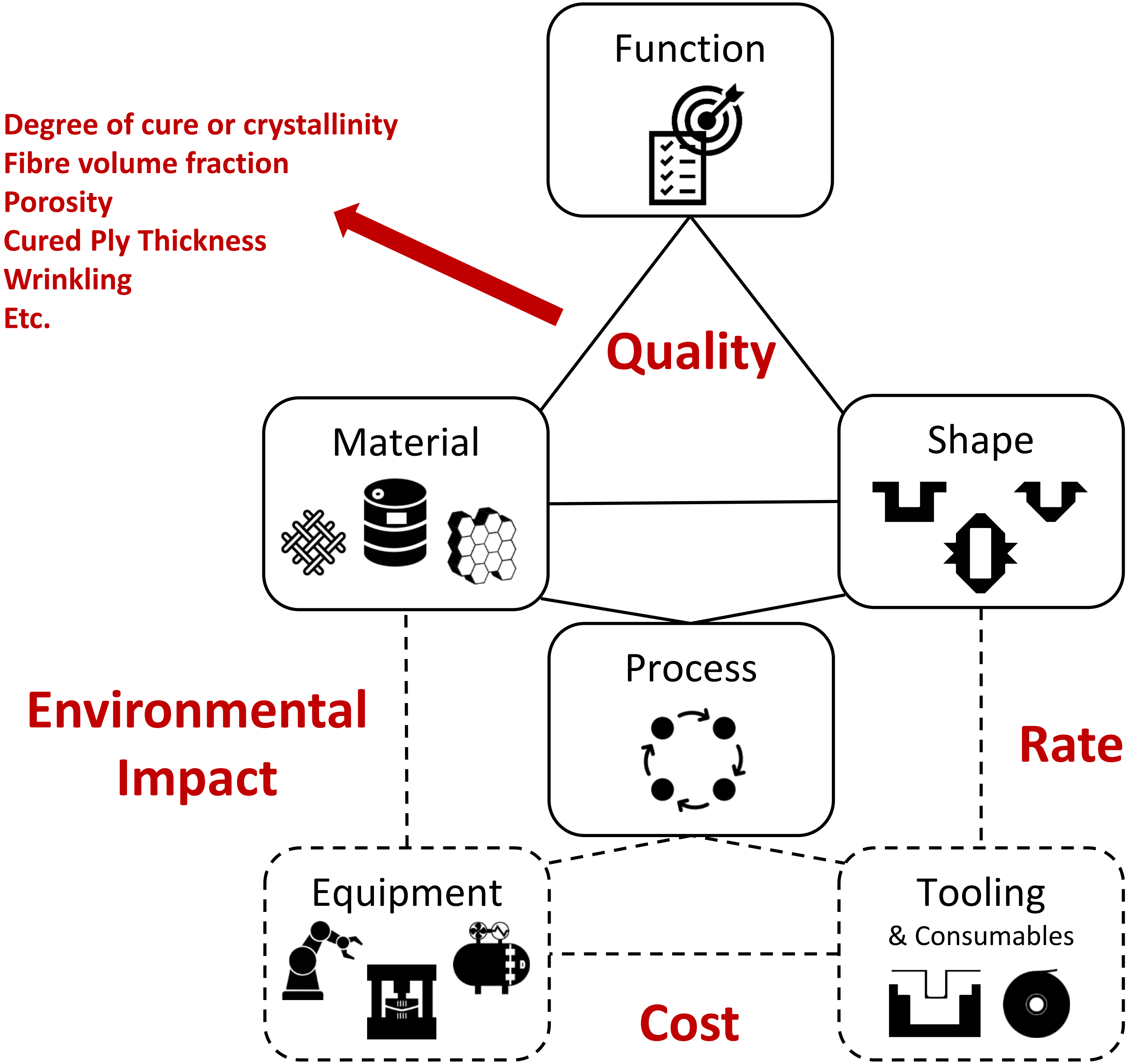
Design

process → microstructure → properties

Manufacturing

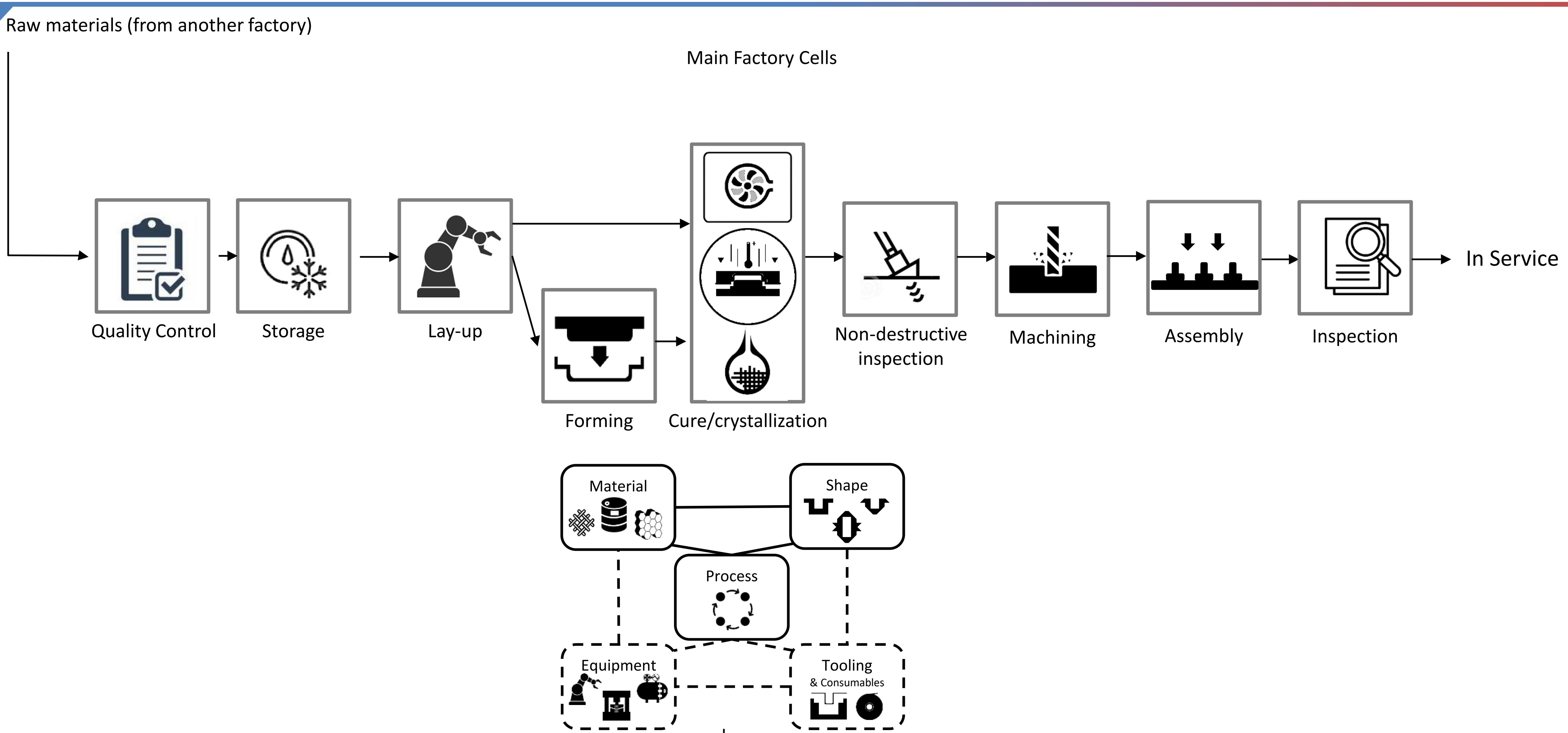
....too limited description
particularly for composites

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



- Development
- Optimization
- Troubleshooting

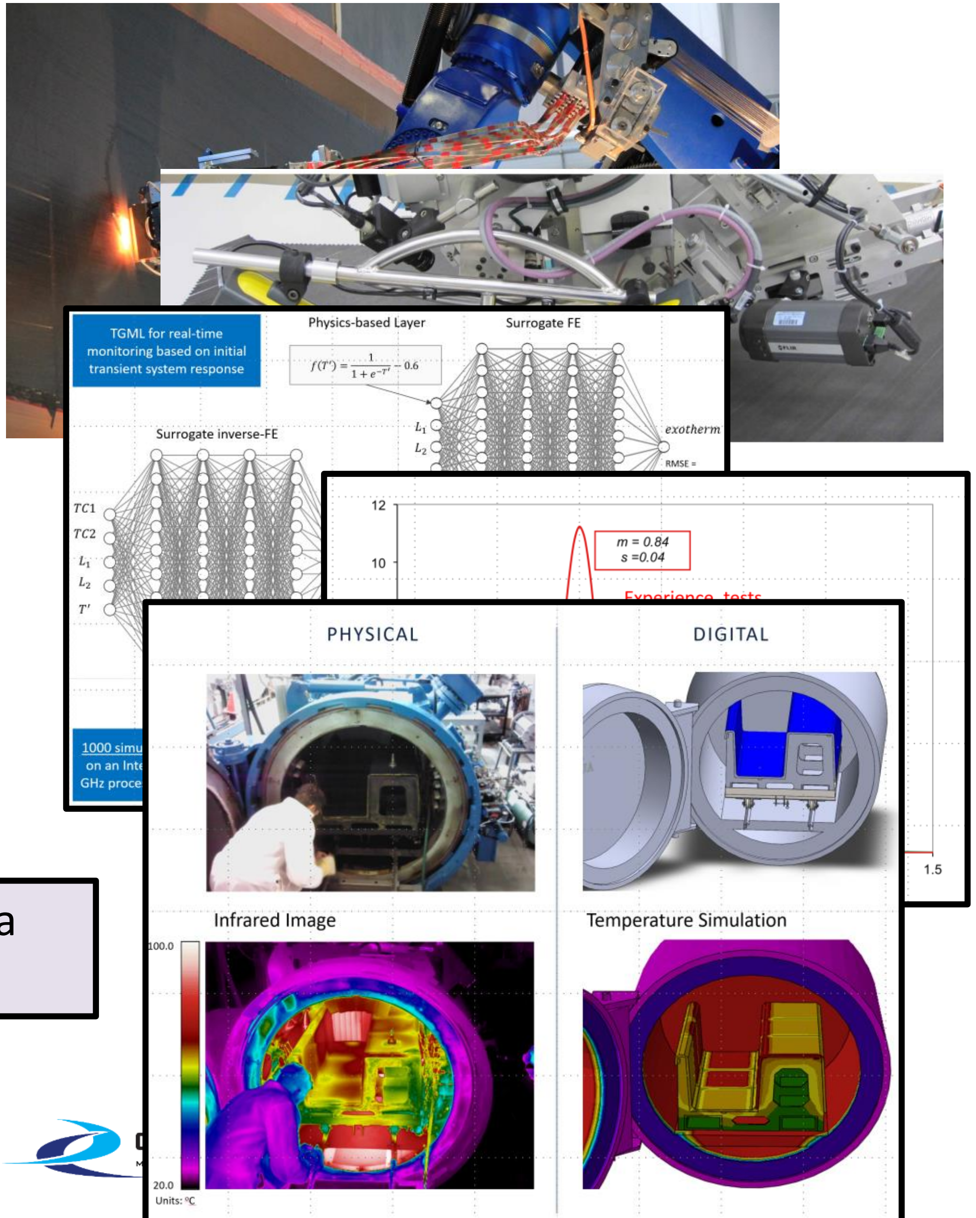
Composites Manufacturing is a Systems Problem



Succeeding with Industry 4.0

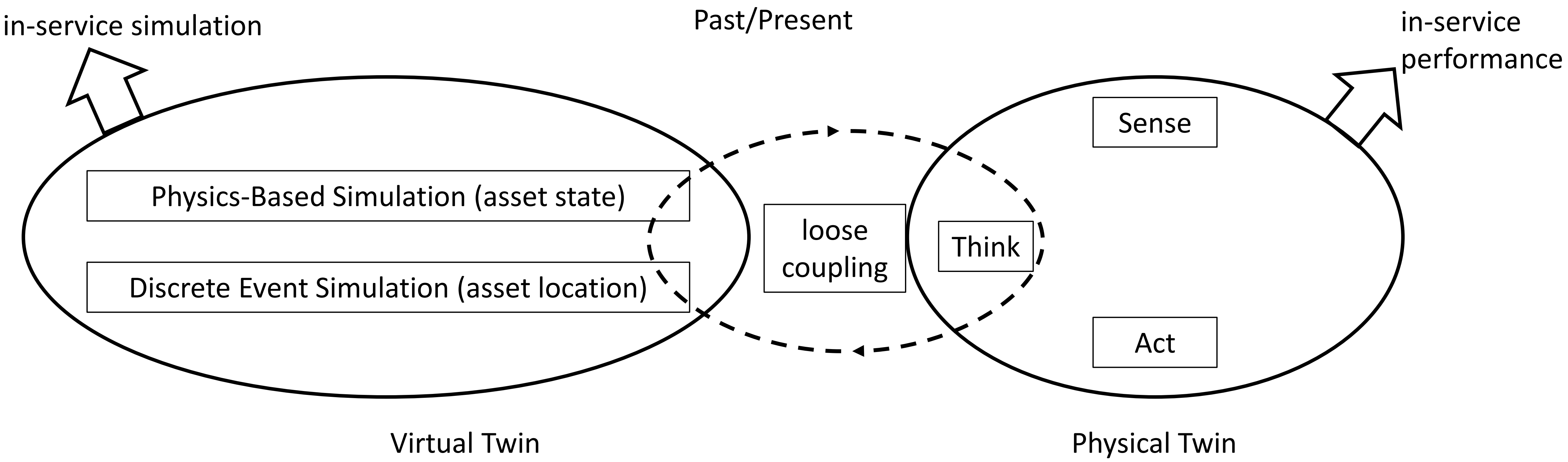
Industry 4.0 is described in many ways, but there are five core enabling technologies you must integrate

- Automation
- Sensing
- Data Sciences including Artificial Intelligence
- Uncertainty Quantification
- Scientific Process Simulation

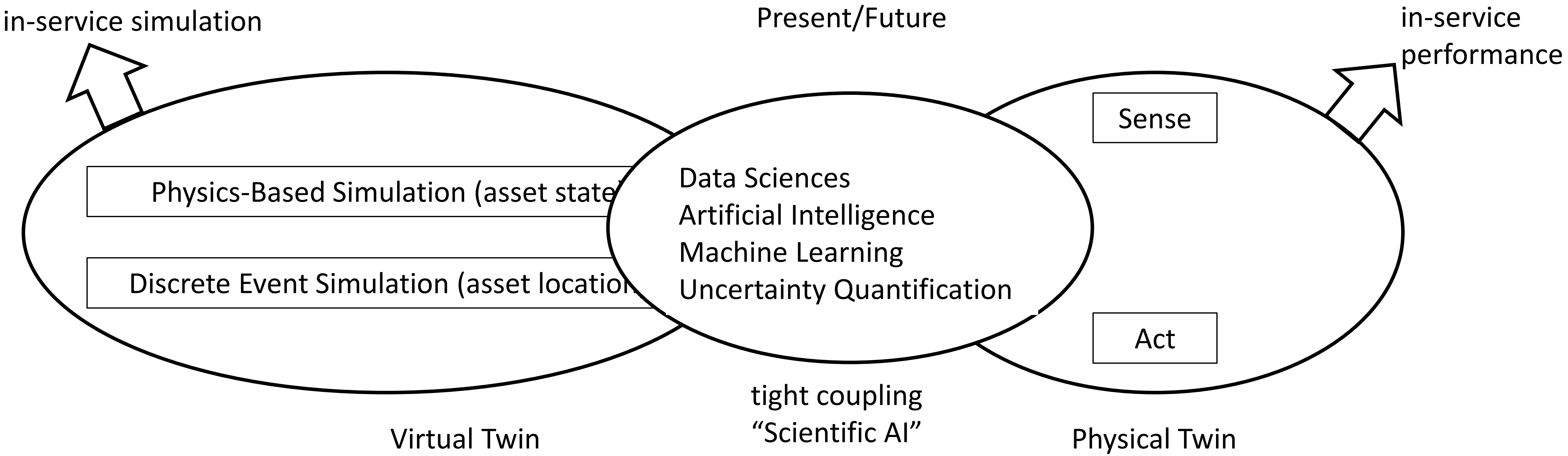


Integration of these core technologies in a coherent manner is critical

The Two Digital Twins: Virtual and Physical Manufacturing



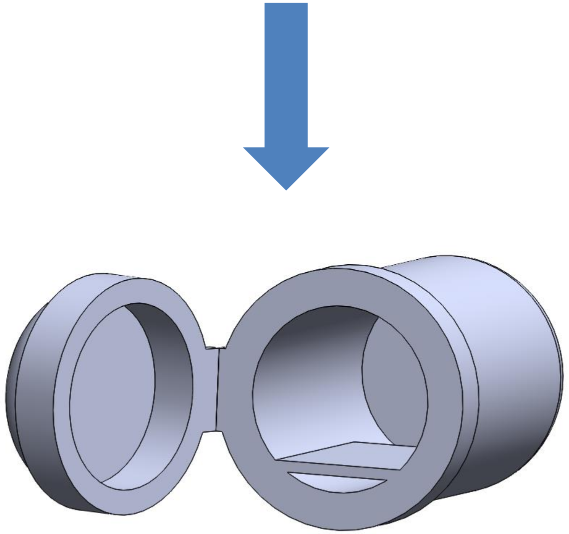
The Two Digital Twins: Virtual and Physical Manufacturing

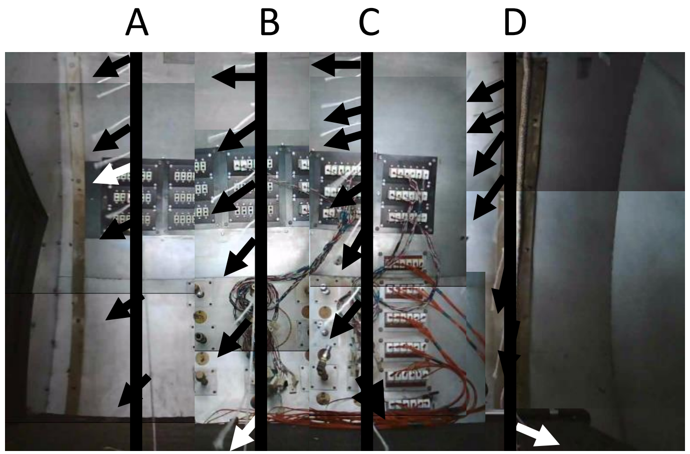


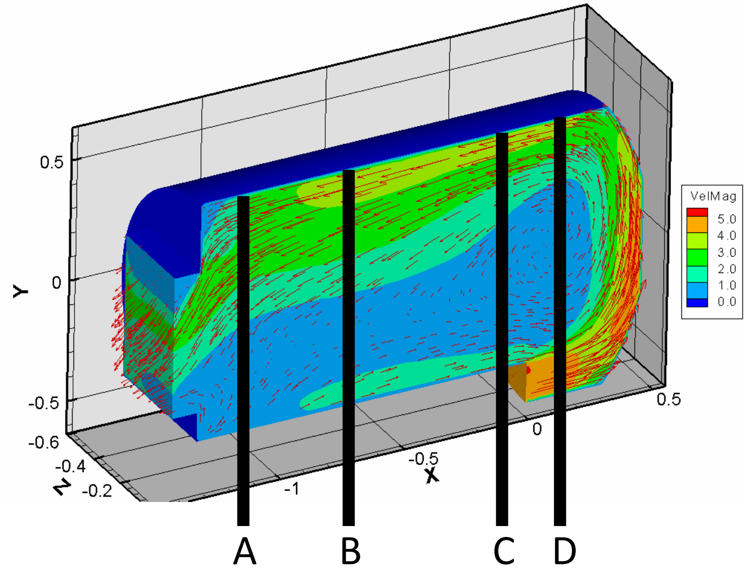
Virtual twin description must be

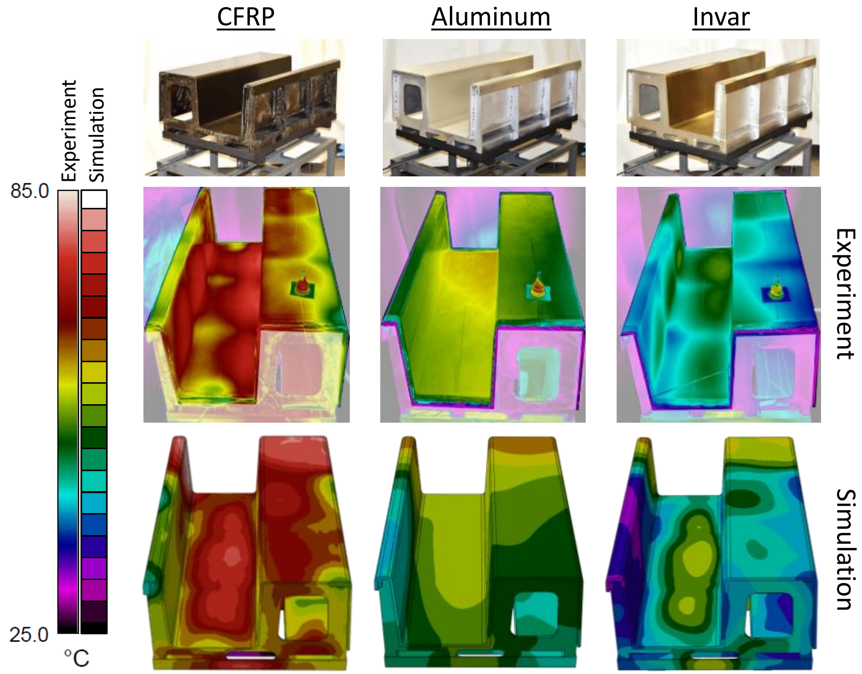
- Integrated across the factory – consider all steps in the process, even if placeholders
- Consistent use of science-based state variable across all cells

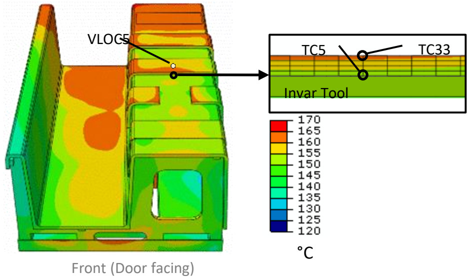
Process Simulation for Thermal Management

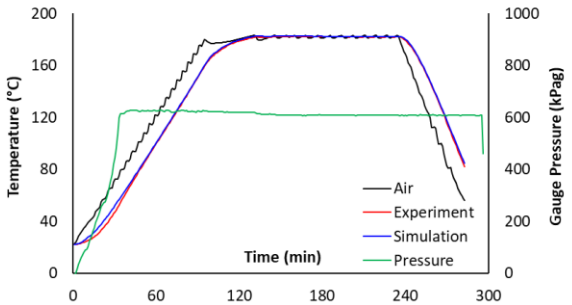












J. Park, Zobeiry N., Mobuchon C., Keulen C., Poursartip A., Tooling materials and their effect on surface thermal gradients, SAMPE Conference, Society for the Advancement of Material and Process Engineering, Seattle, WA, 2017

Zobeiry N., Park J., Poursartip A. (2019) An IR Thermography based method for the evaluation of the thermal response of tooling for composites manufacturing, Journal of Composite Materials, 53(10) 1277–1290.

Project Development with Convergent Tools

Project Initiation
- Specification definition

Conceptual Design
- Development and selection of concepts
- Materials & process selection, rough CAD, etc.

Detailed Design
- Build-out concept to finalize design
- CAD, advanced simulation, etc.
- Virtual prototyping

Physical Prototyping
- Test production systems
- Evaluate product performance

Production
- Scale production systems
- Quality control and assurance

Use
- Life cycle management
- Lessons learned for future improvement
- Repair

Concept Selection

Design Finalization

Product Acceptance

KERMODE
- Material assessment
- Characterization
- Model fitting

RAVEN
- Materials selection
- Cure-cycle design
- Identify and mitigate risks
- FE model setup & analysis
- Part inspection & repair

COMPRO, CPA-TA, & FORMING
- Detailed part and process design
- Optimize part & minimize risks

COHO
- Production system assessment
- Vacuum bag leak detection

CIRT
- Product inspection
- Quality management

Virtual Material Data Sets for Processing

Increasingly available from a variety of sources – open, on demand, Distribution C, proprietary

Resin	Fibre	Manufacturer	Form	Thermo-Chemical	Flow-Compaction		Stress-Deformation	Gas Transport and Porosity	Source
					Fibre Bed	Viscosity			
Duratool 450	CP 200 2x2 Twill	Solvay	Tooling	✓	×	×	✓	×	DoD1
LTM12	CF0700	Solvay	Tooling	✓	×	×	✓	×	DoD1
RS54	E Glass	Toray	Tooling	✓	×	×	✓	×	DoD1
AR4550									
ECK 0.125-									
ECK 0.125-									
Sync									

Resin	Fibre	Manufacturer	Form	Thermo-Chemical	Flow-Compaction		Stress-Deformation	Gas Transport and Porosity	Source
					Fibre Bed	Viscosity			
Nominal Breather		Generic	Other	✓	×	✓	✓	×	Convergent
Nominal Rubber		Generic	Other	✓	×	✓	✓	×	Convergent
Nominal Aluminium 606X		Generic	Tooling	✓	×	✓	✓	×	Convergent
Non									
N									
N									
Non									
HRH-10 3/16-									
HRH-10 3/16-									
3/16-5052-.00									
3/16-5052-.00									
HRP 3/16-4.0									
HRP 3/16-12.									

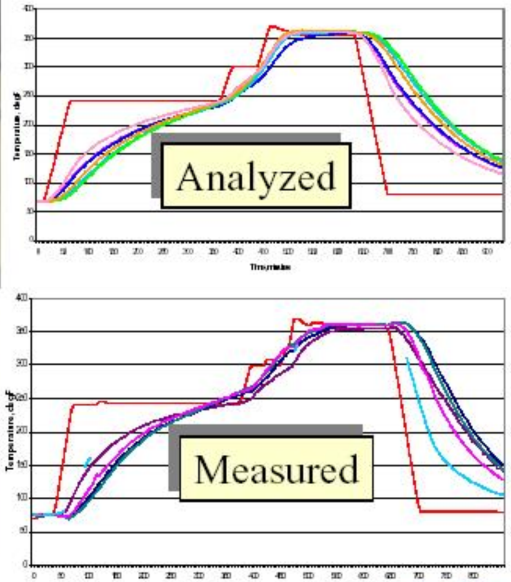
Resin	Fibre	Manufacturer	Form	Thermo-Chemical	Flow-Compaction		Stress-Deformation	Gas Transport and Porosity	Source
					Fibre Bed	Viscosity			
MTM45-1	IM7	Solvay	Prepreg	✓	×	✓	✓	×	TRUST
MTM45-1	-	Solvay	Resin	✓	-	✓	✓	×	TRUST
5250-4									
5250-4									
977-3									
977-3									
977-3	E								
977-3	E Glas								
977-3									
977-3	IM7 T								
977-3	IM7 T								
977-3	IM7 Th								
5320-1									
5320-1									
FM309-1									
M65									
M65									
FM300	Poly								
FM300-05i	Poly								
AF3024									

Resin	Fibre	Manufacturer	Form	Thermo-Chemical	Flow-Compaction		Stress-Deformation	Gas Transport and Porosity	Source
					Fibre Bed	Viscosity			
MTM45-1	HTS5631	ACG	Prepreg	✓	×	✓	×	×	NCAMP/NIAR
5215	T40	Solvay	Prepreg	✓	×	✓	×	×	NCAMP/NIAR
5250-5	T650	Solvay	Prepreg	✓	×	✓	×	×	NCAMP/NIAR
2510U	T700	Toray	Prepreg	✓	×	✓	×	×	NCAMP/NIAR
8552	IM7	Hexcel	Prepreg	✓	×	✓	×	×	NCAMP/NIAR
8552	-	Hexcel	Resin	✓	-	✓	×	×	NCAMP/NIAR
5320-1	IM7	Solvay	Prepreg	✓	×	✓	×	×	Solvay
5320-1	-	Solvay	Resin	✓	-	✓	×	×	Solvay
EP2190	-	Solvay	Resin	✓	×	✓	×	×	Solvay
EP2190	T650	Solvay	Prepreg	✓	×	✓	×	×	Solvay
EP2190	IMS65	Solvay	Prepreg	✓	×	✓	×	×	Solvay
EP2190	HTS45	Solvay	Prepreg	✓	×	✓	×	×	Solvay
FM309-1	-	Solvay	Film Adhesive	✓	-	✓	×	×	Solvay
FM300-2	-	Solvay	Film Adhesive	✓	-	✓	×	×	Solvay
TC250	AS4C	Toray	Prepreg	✓	×	✓	×	×	Toray
TC250	AS4C	Toray	Prepreg	✓	×	✓	×	×	Toray
TC275-1	TR50S	Toray	Prepreg	✓	×	✓	×	×	Toray
TC275-1	HTS40	Toray	Prepreg	✓	×	✓	×	×	Toray
TC380	HM63	Toray	Prepreg	✓	×	✓	×	×	Toray
TC380	IM7	Toray	Prepreg	✓	×	✓	×	×	Toray
TC380	-	Toray	Resin	✓	-	✓	×	×	Toray
TC380	-	Toray	Adhesive	✓	-	✓	×	×	Toray
TC1200 (PEEK)	AS4	Toray	Prepreg	✓	×	✓	×	×	CRN / Convergent

Cure Cycle Optimization

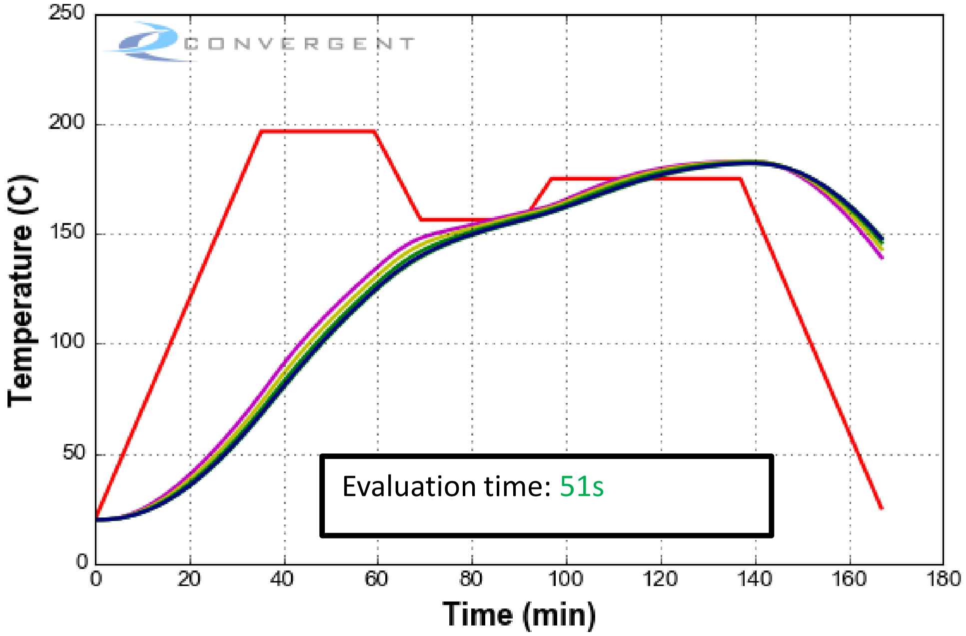
Successful Cure of 3 ½ inch Thick Laminate

First Time - Using Analysis To Specify Cure Cycle



Manual optimization by expert, ~ 8 hours
DARPA AIM-C Program, 2004

RAVEN – TGML Cure Cycle Optimization

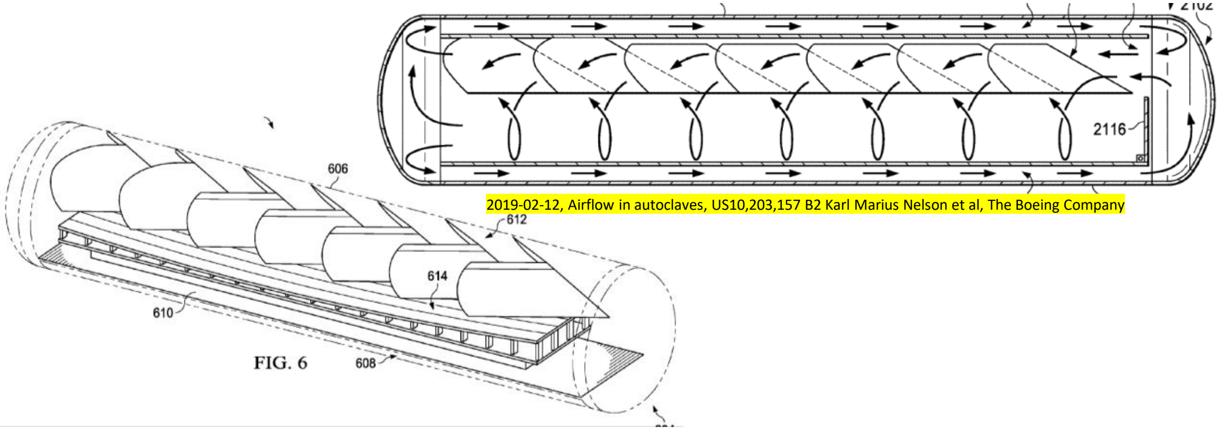


Automated optimization by non-expert, < 1 minute
2022

Standard Practice at Leading OEMs

- 2000s - Boeing 787 fuselage cure cycle designed by Boeing-led team using Convergent COMPRO software

- 2010s – For 777X wing, Boeing also designed the autoclave using simulation



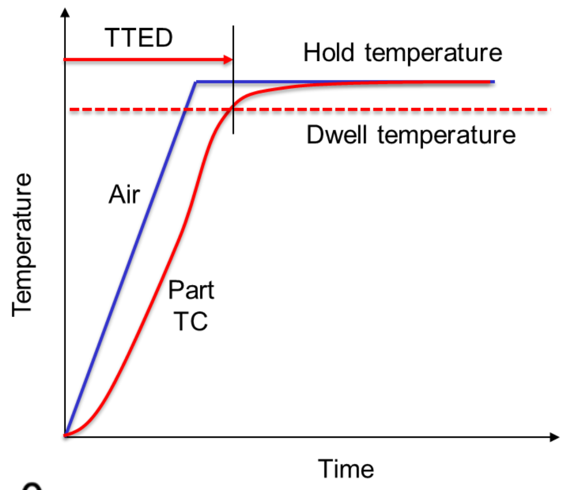
2019-02-12, Airflow in autoclaves, US10,203,157 B2 Karl Marius Nelson et al, The Boeing Company

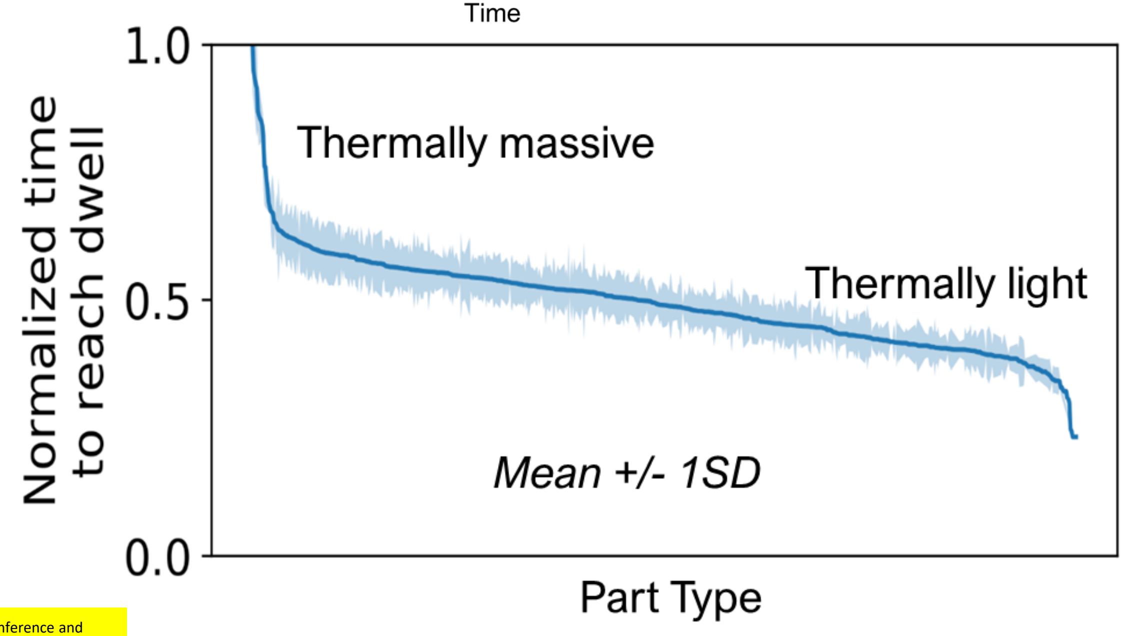
Example: Process Monitoring

- When multiple parts are cured together, autoclave loading is done based on experience.
- This creates unknown heat transfer coefficients which affects temperature histories of parts.
- We are using a combination of
  - Science-based Simulation
  - Theory Guided ML
  - Sensing/IOT
  - Historical Data Analysis

Science-Based Data Analytics: Production Factory

- Nine years of production data from one autoclave was analyzed
- Several hundred different parts
- 4,075 autoclave runs, each with multiple parts
- Total of 75,130 parts
- Over 200,000 thermocouple traces (2 or more per part)
- There is a clear relationship between an individual part and its mean time to reach the cure temperature.
- Method is sufficiently mature now that there is confidence in reducing thermocouple counts in future runs significantly





Stewart A, Fabris J, Terpstra C, Shead M, Fernlund G, Poursartip A, Thermal Analysis of Historical Autoclave Data using Science-Based Data Analytics Methods, SAMPE 2020 Conference and Exhibition, Seattle, United States, May 2020

Example results for 2 cure recipes and 1 AC

	$Model\ probability > 95.0\ \%$	$Model\ probability > 99.0\ \%$
Test set size (# loads)	156	305
Correct predictions	151	304
% Correct predictions	96.8%	99.7%
Dwell failures*	0	0
Avg. parts /run	15	13
Avg. parts to monitor /run	4	3
Avg. % TC reduction /run	73.3%	76.9%
Avg. parts w/o data/run	1	1

- **Dwell failures occur when a part spends less than a fixed amount of time above the dwell temperature*
- *The time in dwell is controlled by the monitored TC with the largest TTED*
- *If the part with the largest TTED is not monitored, dwell failure may occur for this part*

G. Fernlund, M. Shead, A. Floyd, and A. Poursartip, Data mining and science-based predictive analytics for automation of composites processing, ACM-5, Bristol, UK, April 2022

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CIRT

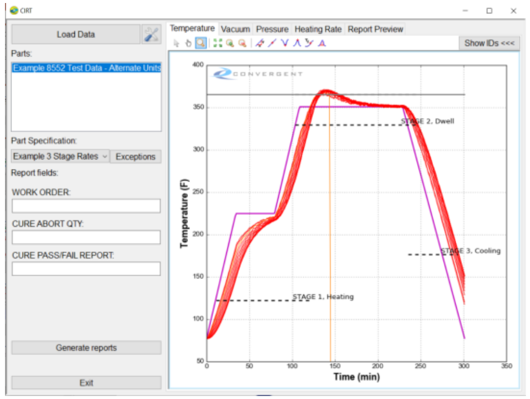
Automated Specification Assessment

CIRT (Composite Inspection Reporting Tool) is used to inspect process data files, assess the data against predefined specification and generate reports detailing how well the part(s) met the requirements.

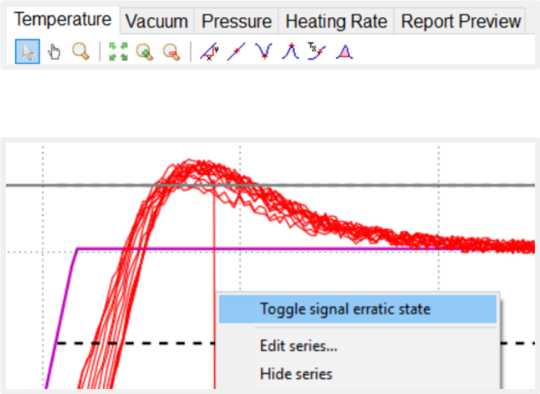
Applications:

- Autoclaves
- Ovens
- Repair
- Presses
- Thermal Processes

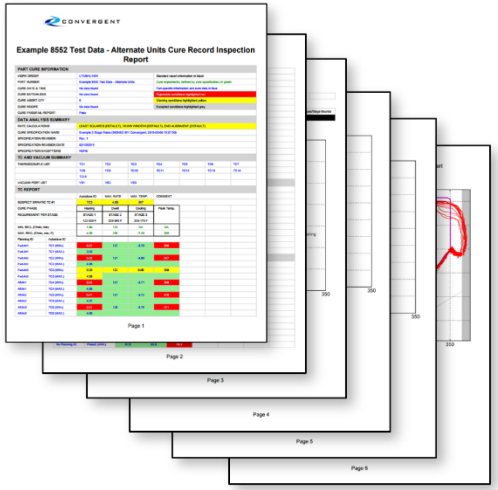
Intuitive Interface



Feature Rich Tools



Automatic Reporting



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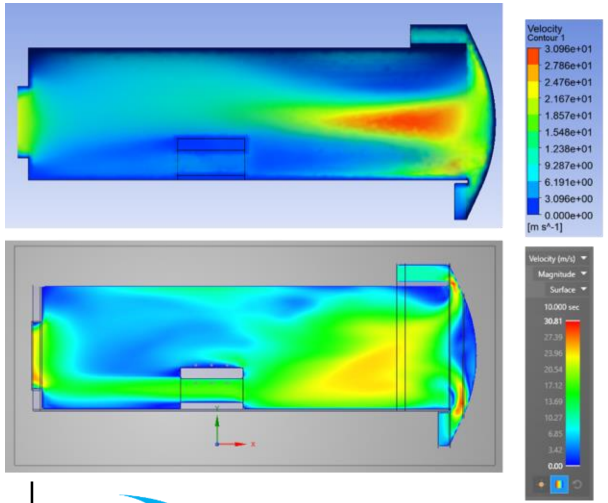
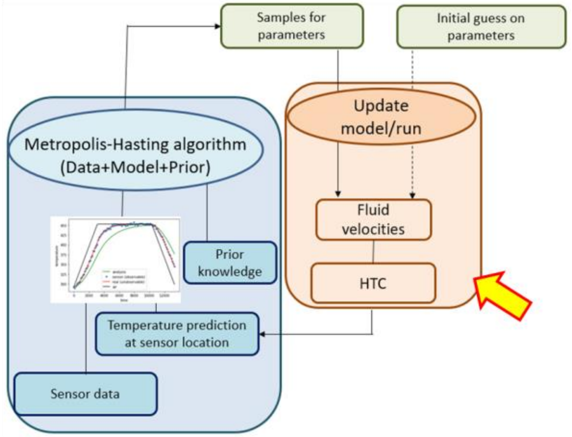
Virtual Thermal Profiling and Virtual Thermocouples

- The critical temperature is in the heart of a structure
- There is no direct sensor technology that can measure this
- Current proxy approaches are NOT rigorous
- We are developing rigorous methods, based on statistical inference, science-based ML surrogate models to give us accurate “virtual thermal profiling” and “virtual thermocouples”
- This means that permanent thermocouples strategically placed on tooling can be used
- This can be done at highly competitive cost and effort with higher reliability and confidence





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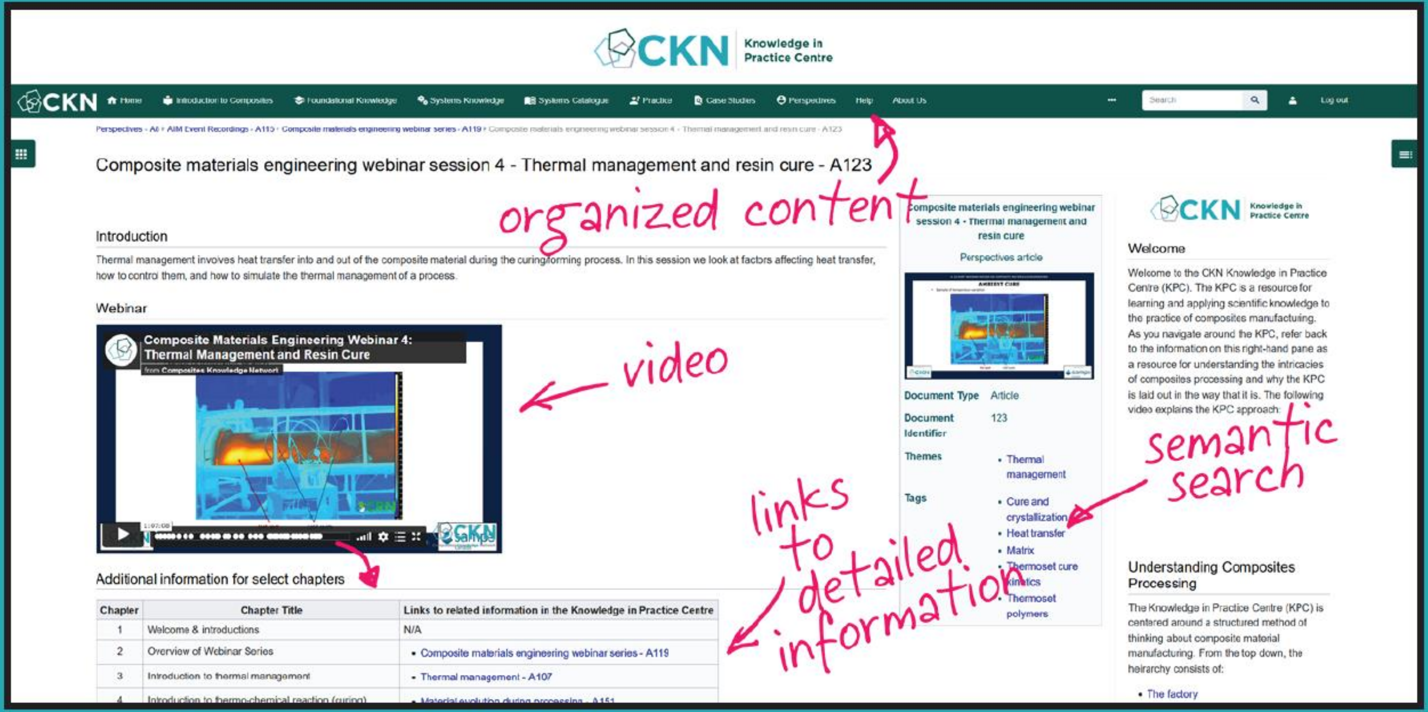
Digital Education

The Knowledge in Practice Centre, an online resource for

Empowering businesses with the composites knowledge they need to succeed



- Trusted and extensive source for composites manufacturing knowledge
- Organized and reviewed science-based content tied to industrial practice
- Multi-level open learning resource
- Webinars, case studies, and practical examples
- Continuously updated

CKN | Composites Knowledge Network

@CompositesKN @CompositesKN

Access at CompositesKN.org/KPC

Summary

- Composites manufacturing is a complex systems problem, and needs an integrated science-based simulation foundation for successful digitalization
- This is the key to enabling significant impact both on and off the factory floor
- This is particularly true for new materials, processes, products, factories, especially for the future where performance-based approaches can be used
- Our approach to manufacturing digitalization includes research (CRN), enabling technologies (Convergent), and education (CKN)

Acknowledgements

- The work presented here has been performed by a very large number of students, colleagues, and collaborators at UBC, CRN, Convergent, and partnering organizations

- In particular, it would not have been possible without the close collaboration of Professor Reza Vaziri

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