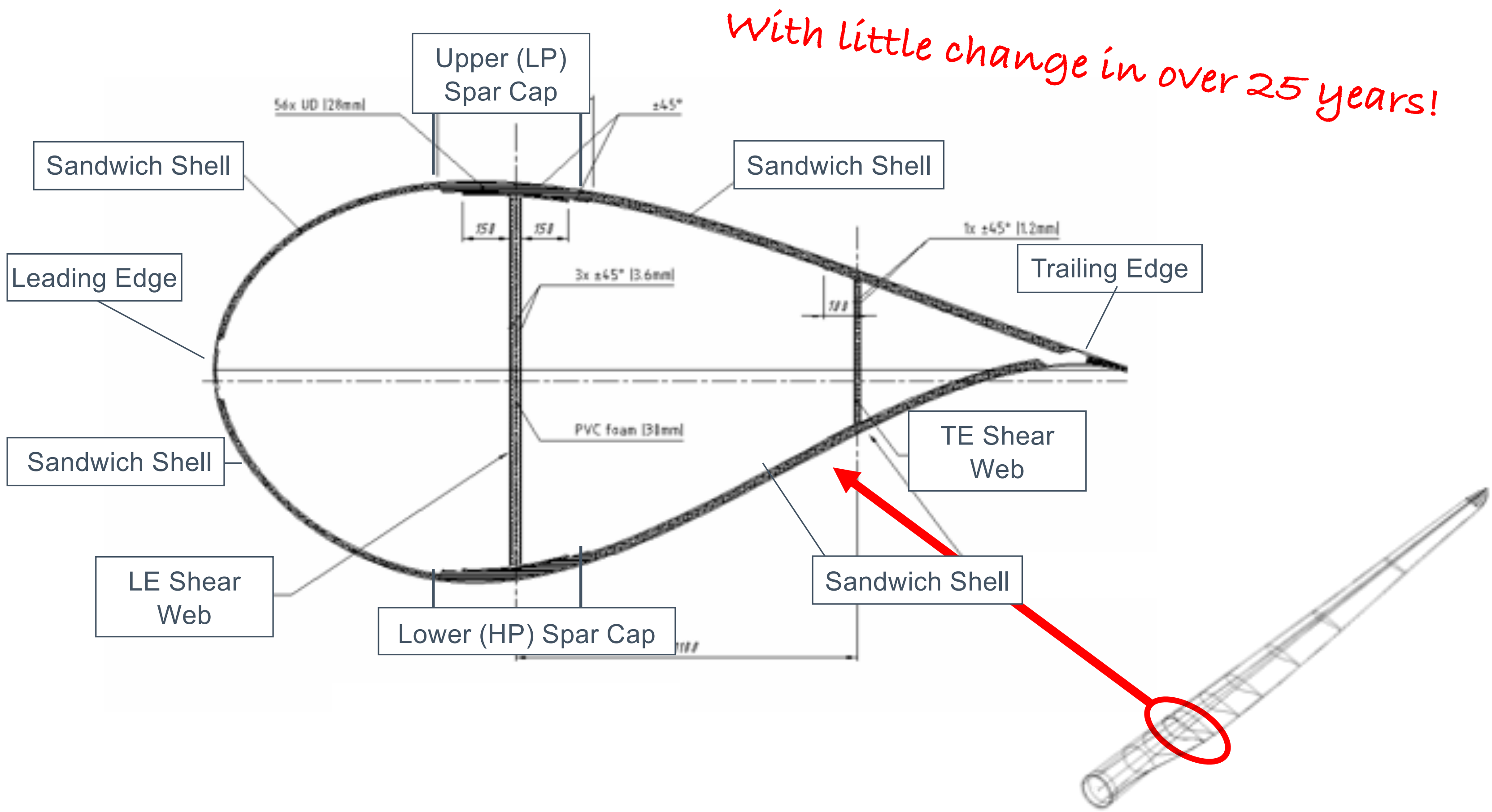
Driving Wind Blade Manufacturing Innovation

Innovation in Materials and Manufacturing

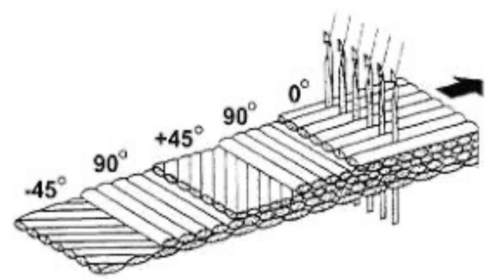
Stephen C. Nolet
Senior Director Innovation & Technology
TPI Composites, Inc.
snolet@tpicomposites.com

Fundamental Design of Composite Wind Blades *is REALLY elegant!*



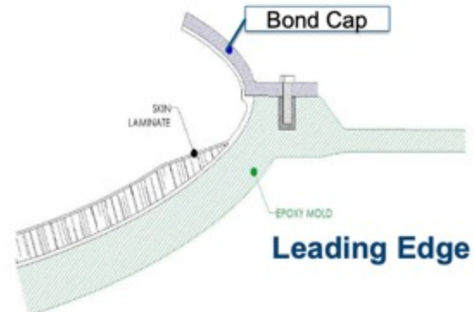
TPI Composites: Largest Independent Manufacturer of Utility-Scale WTB's

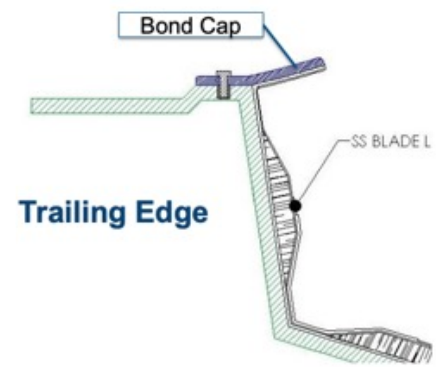
- Nearly 60 years of large-scale composites manufacturing.
- TPI as an early innovator of infusion technologies:
  - Infusion Technology (SCRIMP®)
    - Textile forms from 24oz Woven Roving to Multiaxials with integrated flow fabrics.
    - Sandwich Construction (balsa and foam core replaces honeycomb).
  - Tooling Systems
    - Integrated Mold Heating and Control
    - Precision A-Surface Control
    - Jigs, Fixtures and Assembly Systems
    - Reuseable Silicone Vacuum Bags
  - Advanced Manufacturing Innovation Initiative (AMII, 2009)
    - Trailing Edge Prefabs
    - 3D Laser Projection (ply-templating)
    - Engineered core
    - Rodpack (precursor of pultruded profiles)
    - More: AMII Final



TPI Composites: Largest Independent Manufacturer of Utility-Scale WTB's

- Nearly 60 years of large-scale composites manufacturing.
- TPI as an early innovator of infusion technologies:
  - Infusion Technology (SCRIMP®)
    - Textile forms from 24oz Woven Roving to Multiaxials with integrated flow fabrics.
    - Sandwich Construction (balsa and foam core replaces honeycomb).
  - Tooling Systems
    - Integrated Mold Heating and Control
    - Precision A-Surface Control
    - Jigs, Fixtures and Assembly Systems
    - Reuseable Silicone Vacuum Bags
  - Advanced Manufacturing Innovation Initiative (AMII, 2009)
    - Trailing Edge Prefabs
    - 3D Laser Projection (ply-templating)
    - Engineered core
    - Rodpack (precursor of pultruded profiles)
    - More: AMII Final



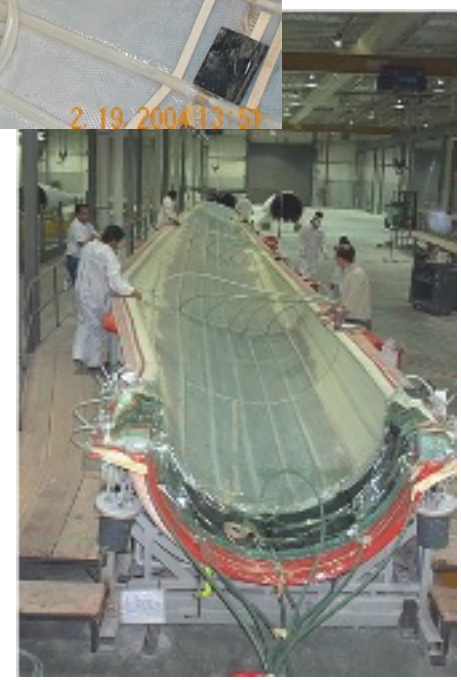


TPI Composites: Largest Independent Manufacturer of Utility-Scale WTB's

- Nearly 60 years of large-scale composites manufacturing.
- TPI as an early innovator of infusion technolo
  - Infusion Technology (SCRIMP®)
    - Textile forms from 24oz Woven Roving to Multiaxia integrated flow fabrics.
    - Sandwich Construction (balsa and foam core replaces
  - Tooling Systems
    - Integrated Mold Heating and Control
    - Precision A-Surface Control
    - Jigs, Fixtures and Assembly Systems
    - Reuseable Silicone Vacuum Bags
  - Advanced Manufacturing Innovation Initiative (AMII, 2009)
    - Trailing Edge Prefabs
    - 3D Laser Projection (ply-templating)
    - Engineered core
    - Rodpack (precursor of pultruded profiles)
    - More: AMII Final

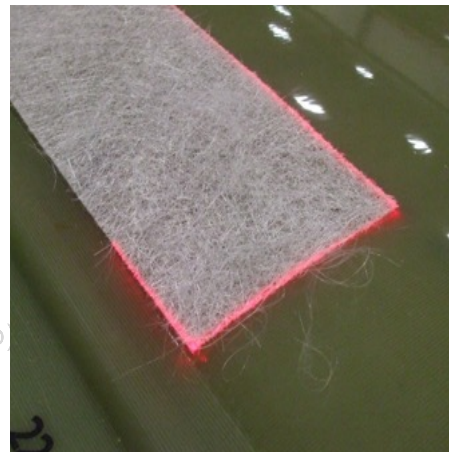
TPI Composites: Largest Independent Manufacturer of Utility-Scale WTB's

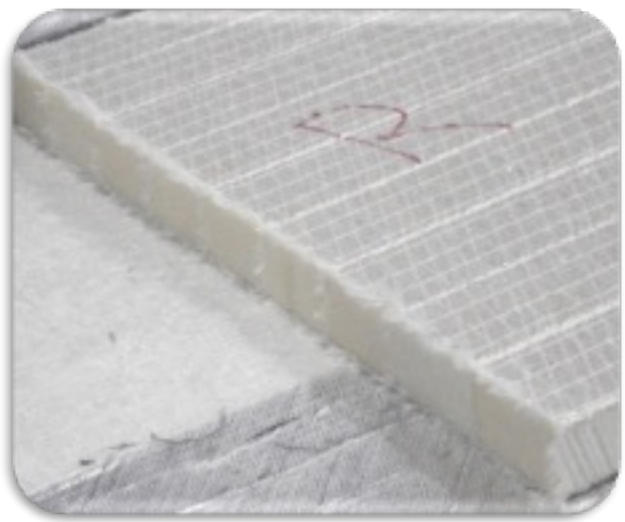
- Nearly 60 years of large-scale composites manufacturing.
- TPI as an early innovator of infusion technologies:
  - Infusion Technology (SCRIMP®)
    - Textile forms from 24oz Woven Roving to Multiaxials with integrated flow fabrics.
    - Sandwich Construction (balsa and foam core replaces honeycomb).
  - Tooling Systems
    - Integrated Mold Heating and Control
    - Precision A-Surface Control
    - Jigs, Fixtures and Assembly Systems
    - Reuseable Silicone Vacuum Bags
  - Advanced Manufacturing Innovation Initiative (AMII, 2009)
    - Trailing Edge Prefabs
    - 3D Laser Projection (ply-templating)
    - Engineered core
    - Rodpack (precursor of pultruded profiles)
    - More: AMII Final



TPI Composites: Largest Independent Manufacturer of Utility-Scale WTB's

- Nearly 60 years of large-scale composites manufacturing.
- TPI as an early innovator of infusion technologies:
  - Infusion Technology (SCRIMP®)
    - Textile forms from 24oz Woven Roving to Multiaxials with integrated flow fabrics.
    - Sandwich Construction (balsa and foam core replaces honeycomb)
  - Tooling Systems
    - Integrated Mold Heating and Control
    - Precision A-Surface Control
    - Jigs, Fixtures and Assembly Systems
    - Reuseable Silicone Vacuum Bags
  - Advanced Manufacturing Innovation Initiative (AMII, 2009)
    - Trailing Edge Prefabs
    - 3D Laser Projection (ply-templating)
    - Engineered core
    - Rodpack (precursor of pultruded profiles)
    - More: AMII Final





In the Past 10+ Years What Has Changed? Challenges Faced in WTB Manufacturing

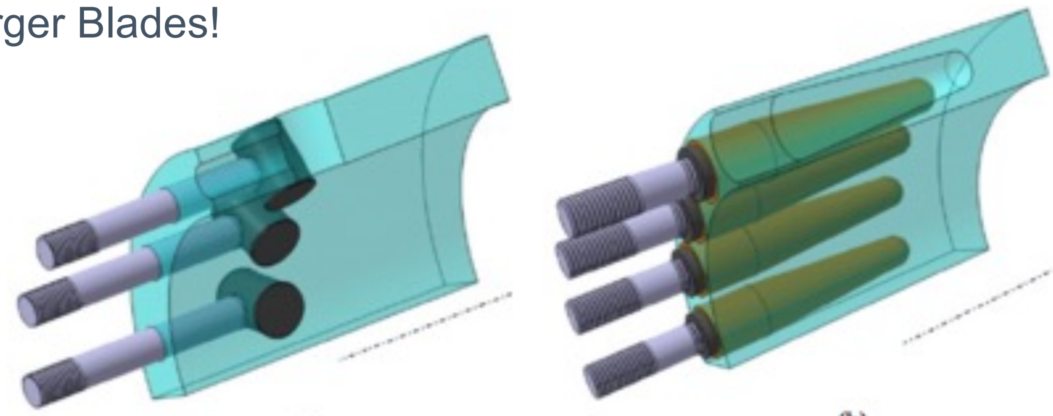
- The chase for Capacity Factor (C_f) => Larger Blades!
  - Blade length and mass.
    - Blade Perimeter and Area.
      - Impact on Quality.
    - Perishable Materials .
      - Out time versus drive for reduced cycle time.
    - Root Attachment.
      - T-Bolts vs Root Inserts.
      - Inserts – Infusion Complexity.
    - Tooling, precision still matters.
      - Bigger blades same tolerances!
    - Blade mass increases fatigue concerns.
      - Focus on quality!!!
  - Cycle-Time Impact.
    - 24 hours remain golden standard.
  - Carbon Fiber is a fact of life.
    - Larger blades become stiffness critical.
    - Edge-wise loading -> carbon reinforcement.
  - Modularity.
    - An opportunity for Owner/Operators.
    - A challenge for blade makers!

In the Past 10+ Years What Has Changed? Challenges Faced in WTB Manufacturing

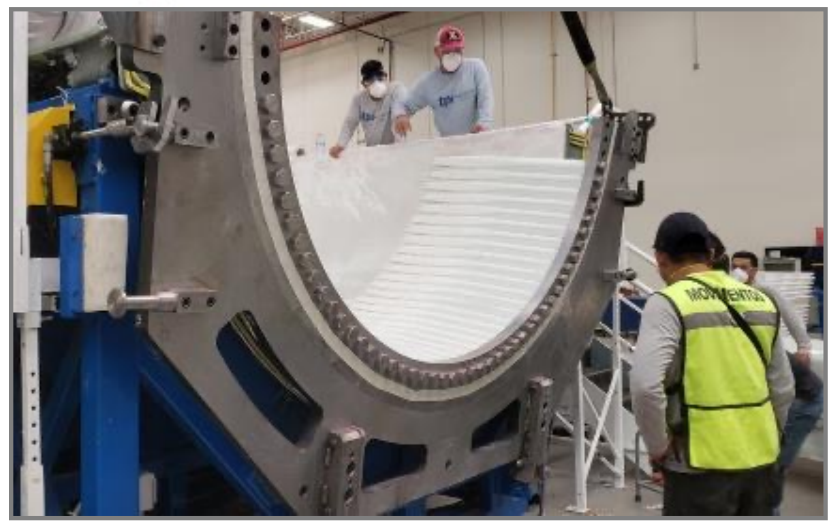
- The chase for Capacity Factor (C_f) => Larger Blades!
  - Blade length and mass.
    - Blade Perimeter and Area.
      - Impact on Quality.
    - Perishable Materials .
      - Out time versus drive for reduced cycle time.
    - Root Attachment.
      - T-Bolts vs Root Inserts.
      - Inserts – Infusion Complexity.
    - Tooling, precision still matters.
      - Bigger blades same tolerances!
    - Blade mass increases fatigue concerns.
      - Focus on quality!!!
  - Cycle-Time Impact.
    - 24 hours remain golden standard.
  - Carbon Fiber is a fact of life.
    - Larger blades become stiffness critical.
    - Edge-wise loading -> carbon reinforcement.
  - Modularity.
    - An opportunity for Owner/Operators.
    - A challenge for blade makers!

In the Past 10+ Years What Has Changed? Challenges Faced in WTB Manufacturing

- The chase for Capacity Factor (C_f) => Larger Blades!
  - Blade length and mass.
    - Blade Perimeter and Area.
      - Impact on Quality.
    - Perishable Materials .
      - Out time versus drive for reduced cycle time.
    - Root Attachment.
      - T-Bolts vs Root Inserts.
      - Inserts – Infusion Complexity.
    - Tooling, precision still matters.
      - Bigger blades same tolerances!
    - Blade mass increases fatigue concerns.
      - Focus on quality!!!
  - Cycle-Time Impact.
    - 24 hours remain golden standard.
  - Carbon Fiber is a fact of life.
    - Larger blades become stiffness critical.
    - Edge-wise loading -> carbon reinforcement.
  - Modularity.
    - An opportunity for Owner/Operators.
    - A challenge for blade makers!

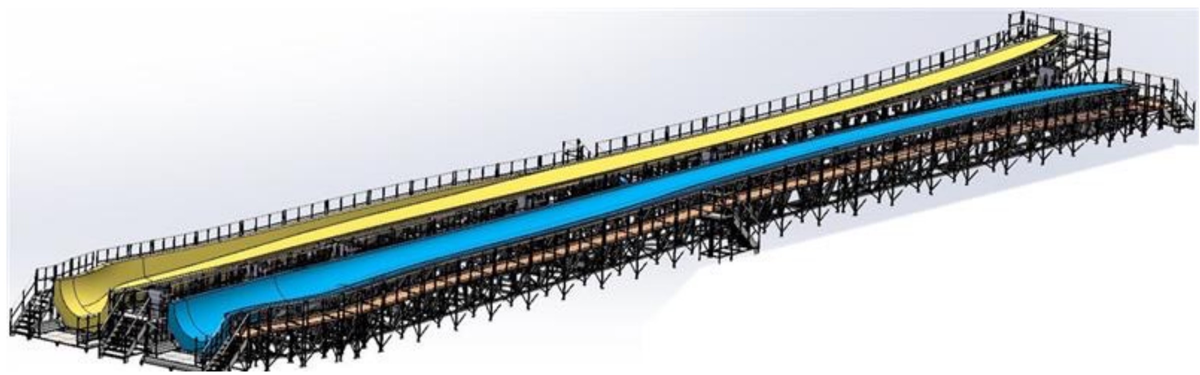


(a) (b)



In the Past 10+ Years What Has Changed? Challenges Faced in WTB Manufacturing

- The chase for Capacity Factor (C_f) => Larger Blades!
  - Blade length and mass.
    - Blade Perimeter and Area.
      - Impact on Quality.
    - Perishable Materials .
      - Out time versus drive for reduced cycle time.
    - Root Attachment.
      - T-Bolts vs Root Inserts.
      - Inserts – Infusion Complexity.
    - Tooling, precision still matters.
      - Bigger blades same tolerances!
    - Blade mass increases fatigue concerns.
      - Focus on quality!!!
  - Cycle-Time Impact.
    - 24 hours remain golden standard.
  - Carbon Fiber is a fact of life.
    - Larger blades become stiffness critical.
    - Edge-wise loading -> carbon reinforcement.
  - Modularity.
    - An opportunity for Owner/Operators.
    - A challenge for blade makers!

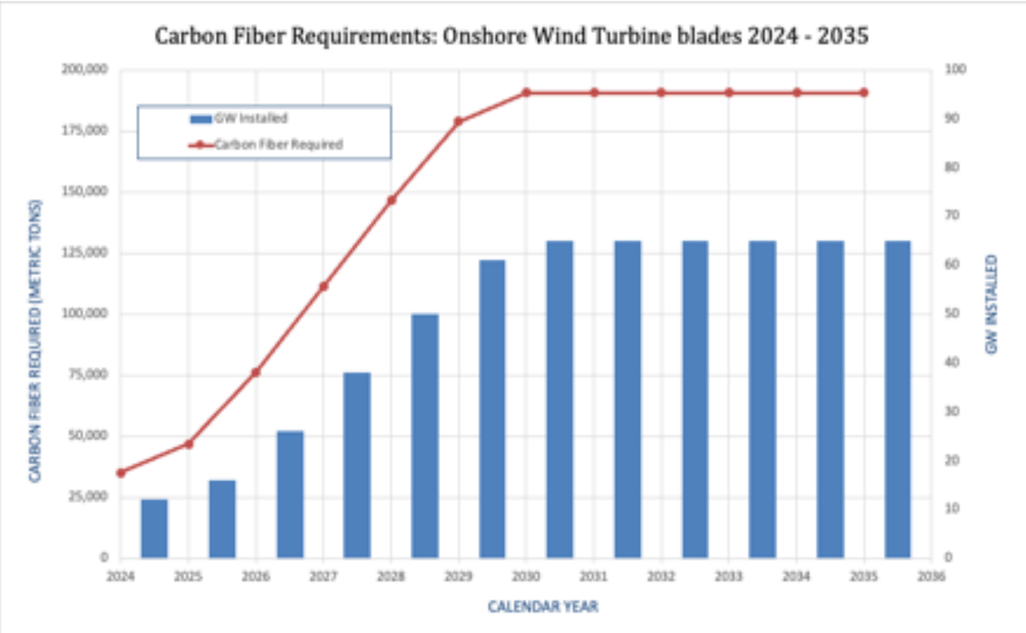


In the Past 10+ Years What Has Changed? Challenges Faced in WTB Manufacturing

- The chase for Capacity Factor (C_f) => Larger Blades!
  - Blade length and mass.
    - Blade Perimeter and Area.
      - Impact on Quality.
    - Perishable Materials .
      - Out time versus drive for reduced cycle time.
    - Root Attachment.
      - T-Bolts vs Root Inserts.
      - Inserts – Infusion Complexity.
    - Tooling, precision still matters.
      - Bigger blades same tolerances!
    - Blade mass increases fatigue concerns.
      - Focus on quality!!!
  - Cycle-Time Impact.
    - 24 hours remain golden standard.
  - Carbon Fiber is a fact of life.
    - Larger blades become stiffness critical.
    - Edge-wise loading -> carbon reinforcement.
  - Modularity.
    - An opportunity for Owner/Operators.
    - A challenge for blade makers!

In the Past 10+ Years What Has Changed? Challenges Faced in WTB Manufacturing

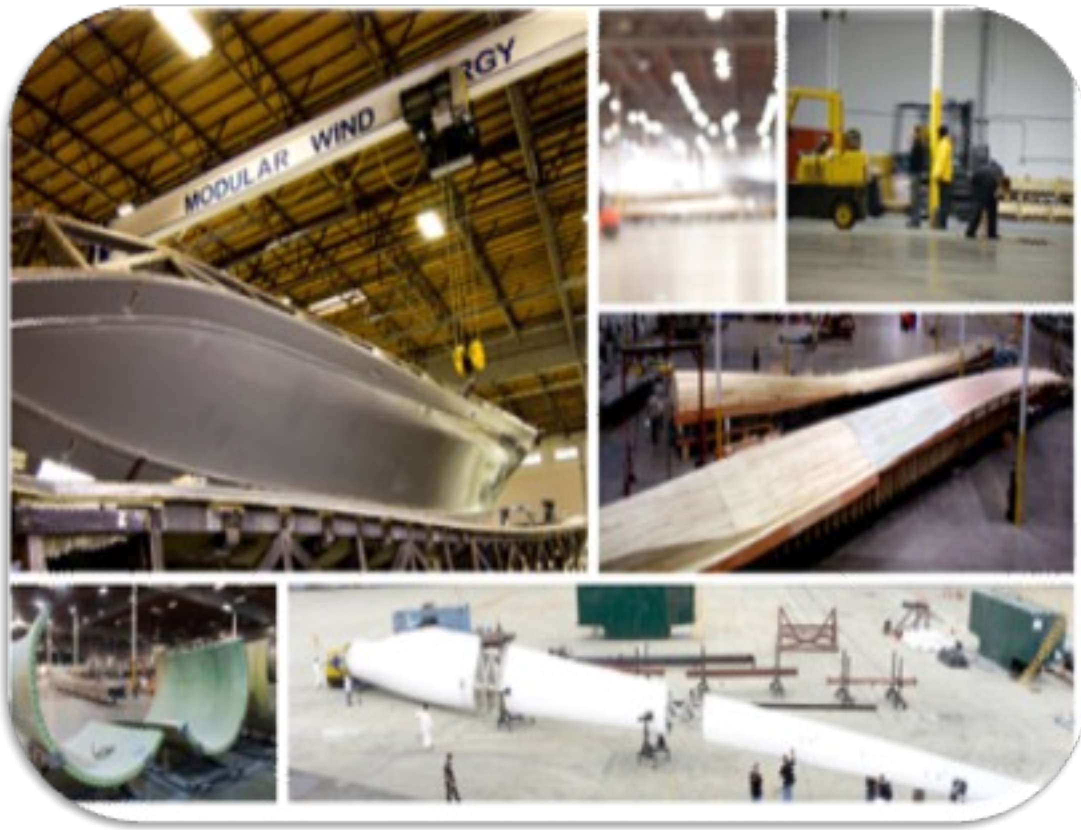
- The chase for Capacity Factor (C_f) => Larger Blades!
  - Blade length and mass.
    - Blade Perimeter and Area.
      - Impact on Quality.
    - Perishable Materials .
      - Out time versus drive for reduced cycle time.
    - Root Attachment.
      - T-Bolts vs Root Inserts.
      - Inserts – Infusion Complexity.
    - Tooling, precision still matters.
      - Bigger blades same tolerances!
    - Blade mass increases fatigue concerns.
      - Focus on quality!!!
  - Cycle-Time Impact.
    - 24 hours remain golden standard.
  - Carbon Fiber is a fact of life.
    - Larger blades become stiffness critical.
    - Edge-wise loading -> carbon reinforcement.
  - Modularity.
    - An opportunity for Owner/Operators.
    - A challenge for blade makers!



Nolet, S.C., "*Evolution of Wind Blade Manufacturing*", Carbon Fiber 23, Composites World, November 2023.

In the Past 10+ Years What Has Changed? Challenges Faced in WTB Manufacturing

- The chase for Capacity Factor (C_f) => Larger Blades!
  - Blade length and mass.
    - Blade Perimeter and Area.
      - Impact on Quality.
    - Perishable Materials .
      - Out time versus drive for reduced cycle time.
    - Root Attachment.
      - T-Bolts vs Root Inserts.
      - Inserts – Infusion Complexity.
    - Tooling, precision still matters.
      - Bigger blades same tolerances!
    - Blade mass increases fatigue concerns.
      - Focus on quality!!!
  - Cycle-Time Impact.
    - 24 hours remain golden standard.
  - Carbon Fiber is a fact of life.
    - Larger blades become stiffness critical.
    - Edge-wise loading -> carbon reinforcement.
  - Modularity.
    - An opportunity for Owner/Operators.
    - A challenge for blade makers!

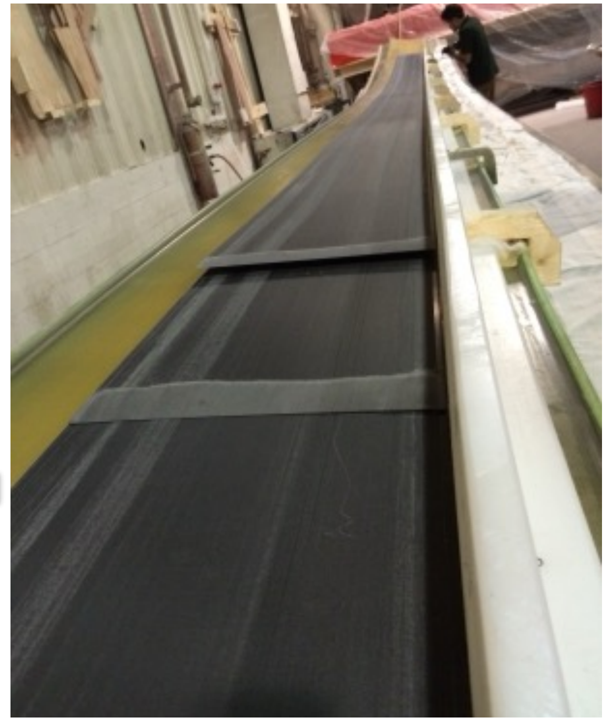


Today's Innovations are (arguably) "Evolutionary"

- Today's Innovations
  - Integration of "prefabrications".
    - Root, Spars, Trailing-Edge & Leading-Edge Prefab's
    - Pultruded Spar Caps
      - Evolution of the RodPack?
  - Model based Manufacturing
    - Ply-by-ply Modeling
    - Core Geometry Extraction, More to do!
  - T-Bolts to root inserts, multitude of methods
    - Increasing root stud density
    - Increasing infusion complexity (and cycle time)
  - What about AUTOMATION???
    - Ply cutting
    - Blade finishing (root drilling, flange trim, surface fairing, scuff sanding/paint prep, robotic painting, etc.)
      - Klingspor
      - Temple Allen
      - Others/Custom
    - Automation in molding: It's CT (and cost).
      - Ingersoll, MAG/Fives, Danobat, MTorres

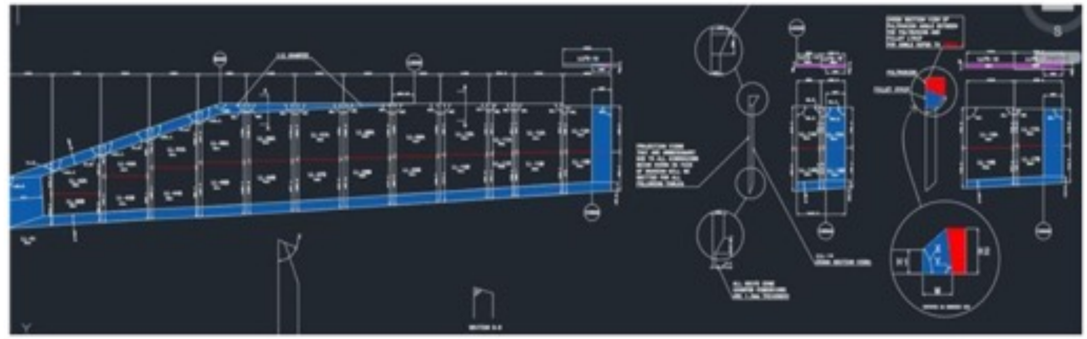
Today's Innovations are (arguably) "Evolutionary"

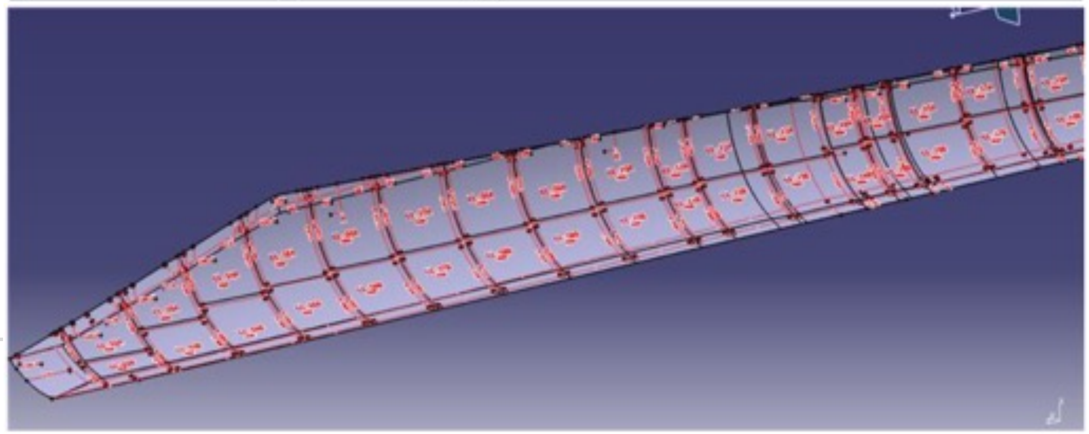
- Today's Innovations
  - Integration of "prefabrications".
    - Root, Spars, Trailing-Edge & Leading-Edge Prefab's
    - Pultruded Spar Caps
      - Evolution of the RodPack?
  - Model based Manufacturing
    - Ply-by-ply Modeling
    - Core Geometry Extraction, More to do!
  - T-Bolts to root inserts, multitude of methods
    - Increasing root stud density
    - Increasing infusion complexity (and cycle time)
  - What about AUTOMATION???
    - Ply cutting
    - Blade finishing (root drilling, flange trim, surface fairing, scuff sanding/paint prep, robotic painting, etc.)
      - Klingspor
      - Temple Allen
      - Others/Custom
    - Automation in molding: It's CT (and cost).
      - Ingersoll, MAG/Fives, Danobat, MTorres



Today's Innovations are (arguably) "Evolutionary"

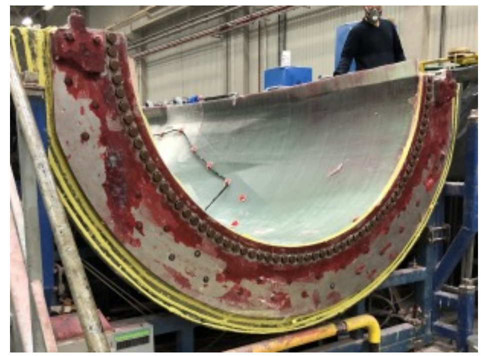
- Today's Innovations
  - Integration of "prefabrications".
    - Root, Spars, Trailing-Edge & Leading-Edge Prefab's
    - Pultruded Spar Caps
      - Evolution of the RodPack?
  - Model based Manufacturing
    - Ply-by-ply Modeling
    - Core Geometry Extraction, More to do!
  - T-Bolts to root inserts, multitude of methods
    - Increasing root stud density
    - Increasing infusion complexity (and cycle time)
  - What about AUTOMATION???
    - Ply cutting
    - Blade finishing (root drilling, flange trim, surface fairing, scuff sanding/paint prep, robotic painting, etc.
      - Klingspor
      - Temple Allen
      - Others/Custom
    - Automation in molding: It's CT (and cost).
      - Ingersoll, MAG/Fives, Danobat, MTorres

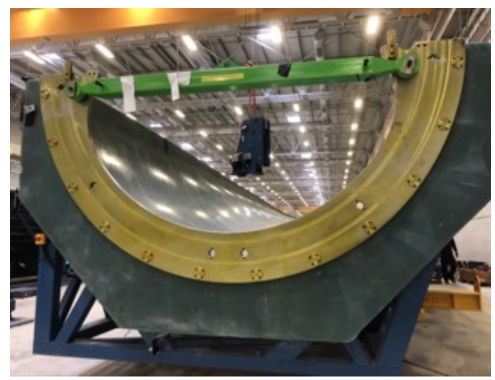


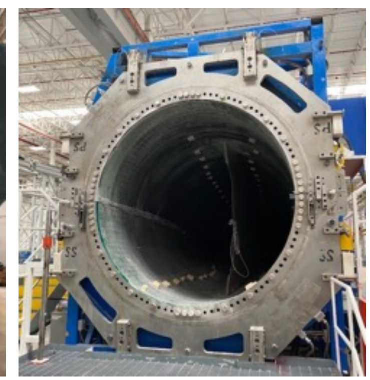


Today's Innovations are (arguably) "Evolutionary"

- Today's Innovations
  - Integration of "prefabrications".
    - Root, Spars, Trailing-Edge & Leading-Edge Prefab's
    - Pultruded Spar Caps
      - Evolution of the RodPack?
  - Model based Manufacturing
    - Ply-by-ply Modeling
    - Core Geometry Extraction, More to do!
  - T-Bolts to root inserts, multitude of methods
    - Increasing root stud density
    - Increasing infusion complexity (and cycle time)
  - What about AUTOMATION???
    - Ply cutting
    - Blade finishing (root drilling, flange trim, surface fairing, scuff sanding/paint prep, robotic painting, etc.)
      - Klingspor
      - Temple Allen
      - Others/Custom
    - Automation in molding: It's CT (and cost).
      - Ingersoll, MAG/Fives, Danobat, MTorres







Today’s Innovations are (arguably) ”Evolutionary”

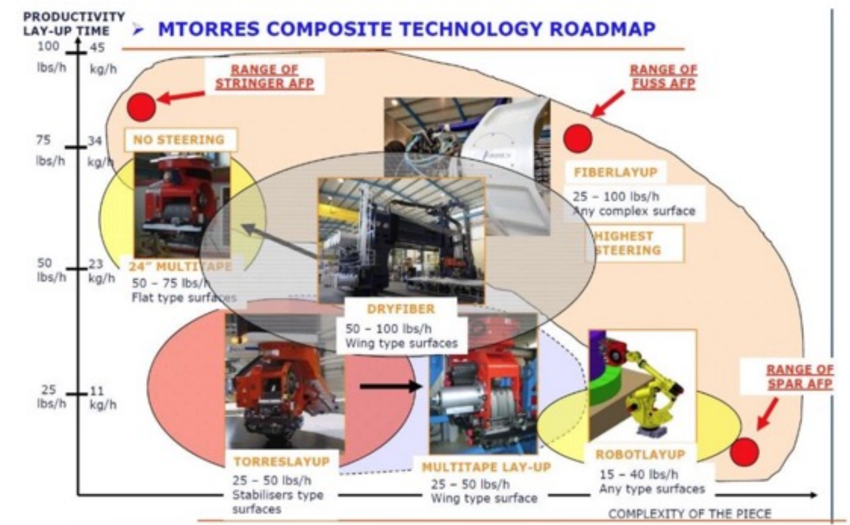
- Today’s Innovations
  - Integration of “prefabrications”.
    - Root, Spars, Trailing-Edge & Leading-Edge Prefab’s
    - Pultruded Spar Caps
      - Evolution of the RodPack?
  - Model based Manufacturing
    - Ply-by-ply Modeling
    - Core Geometry Extraction, More to do!
  - T-Bolts to root inserts, multitude of methods
    - Increasing root stud density
    - Increasing infusion complexity (and cycle time)
  - What about AUTOMATION???
    - Ply cutting
    - Blade finishing (root drilling, flange trim, surface fairing, scuff sanding/paint prep, robotic painting, etc.)
      - Klingspor
      - Temple Allen
      - Others/Custom
    - Automation in molding: It’s CT (and cost).
      - Ingersoll, MAG/Fives, Danobat, MTorres

Klingspor MSS 800 3.0 Blade Sanding System.

Temple Allen EMMA® robotic sand, grind, polish robot.

Today's Innovations are (arguably) "Evolutionary"

- Today's Innovations
  - Integration of "prefabrications".
    - Root, Spars, Trailing-Edge & Leading-Edge Prefab's
    - Pultruded Spar Caps
      - Evolution of the RodPack?
  - Model based Manufacturing
    - Ply-by-ply Modeling
    - Core Geometry Extraction, More to do!
  - T-Bolts to root inserts, multitude of methods
    - Increasing root stud density
    - Increasing infusion complexity (and cycle time)
  - What about AUTOMATION???
    - Ply cutting
    - Blade finishing (root drilling, flange trim, surface fairing, scuff sanding/paint prep, robotic painting, etc.)
      - Klingspor
      - Temple Allen
      - Others/Custom
    - Automation in molding: It's CT (and cost).
      - Ingersoll, MAG/Fives, Danobat, MTorres



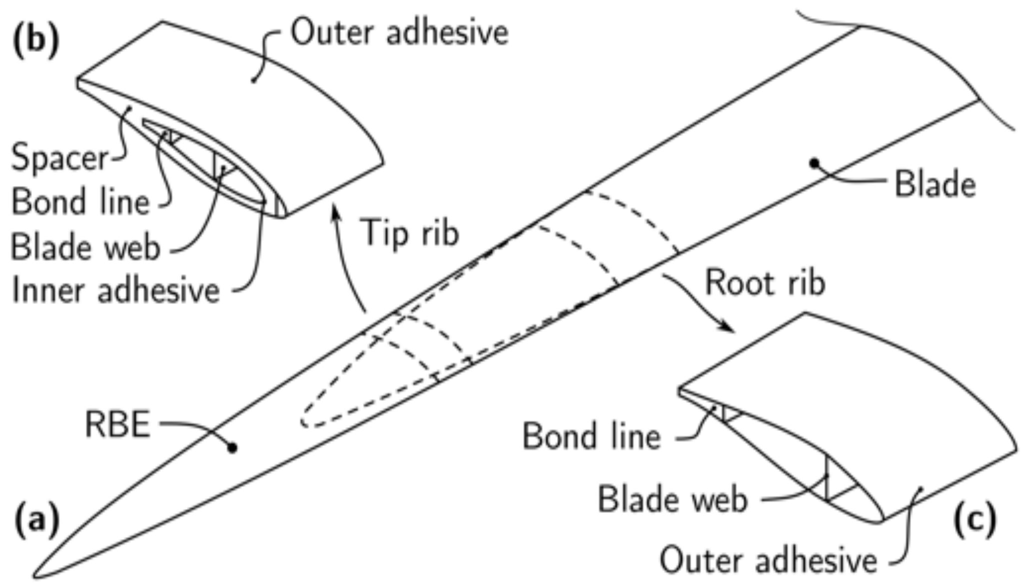
Looking Forward: Where is Innovation Blooming?

- Additive Manufacturing.
  - Blades and Blade Components.
    - Deposition rate is primary impediment (IMHO).
    - Extensible blade tips (making AM more realistic).
    - TPI engaged with the Labs and Academia on FOA 2960 projects.
    - ”Swarm 3D printing”??
  - Tooling
    - MEGAPRINT
      - Modularity
  - What about Core Materials?
    - NREL leading FOA 2252 project, materials challenge?

photo: BigRep ONE

Looking Forward: Where is Innovation Blooming?

- Additive Manufacturing.
  - Blades and Blade Components.
    - Deposition rate is primary impediment (IMHO).
    - Extensible blade tips (making AM more realistic).
    - TPI engaged with the Labs and Academia on FOA 2960 projects.
    - ”Swarm 3D printing”??
  - Tooling
    - MEGAPRINT
      - Modularity
  - What about Core Materials?
    - NREL leading FOA 2252 project, materials challenge?



Malo Rosemeier and Matthias Saathoff, Wind Energ. Sci., 5, 897-909, https://doi.org/10.5194/wes-5-897-2020, 2020

Looking Forward: Where is Innovation Blooming?

- Additive Manufacturing.
  - Blades and Blade Components.
    - Deposition rate is primary impediment (IMHO).
    - Extensible blade tips (making AM more realistic).
    - TPI engaged with the Labs and Academia on FOA 2960 projects.
    - ”Swarm 3D printing”??
  - Tooling
    - MEGAPRINT
      - Modularity
  - What about Core Materials?
    - NREL leading FOA 2252 project, materials challenge?

Fabrication of Fully Recyclable Wind Turbine Blades via Multi-Axis Additive Manufacturing

DOE-FOA-0002960: Large Wind Turbine Materials and Manufacturing
Topic #1: Large Wind Blade Additive Manufacturing

Looking Forward: Where is Innovation Blooming?

- Additive Manufacturing.
  - Blades and Blade Components.
    - Deposition rate is primary impediment (IMHO).
    - Extensible blade tips (making AM more realistic).
    - TPI engaged with the Labs and Academia on FOA 2960 projects.
    - ”Swarm 3D printing”??
  - Tooling
    - MEGAPRINT
      - Modularity
  - What about Core Materials?
    - NREL leading FOA 2252 project, materials challenge?

Looking Forward: Where is Innovation Blooming?

- Additive Manufacturing.
  - Blades and Blade Components.
    - Deposition rate is primary impediment (IMHO).
    - Extensible blade tips (making AM more realistic).
    - TPI engaged with the Labs and Academia on FOA 2960 projects.
    - ”Swarm 3D printing”??
  - Tooling
    - MEGAPRINT
      - Modularity
  - What about Core Materials?
    - NREL leading FOA 2252 project, materials challenge?

photo: Oak Ridge National Lab & TPI Composites

Looking Forward: Where is Innovation Blooming?

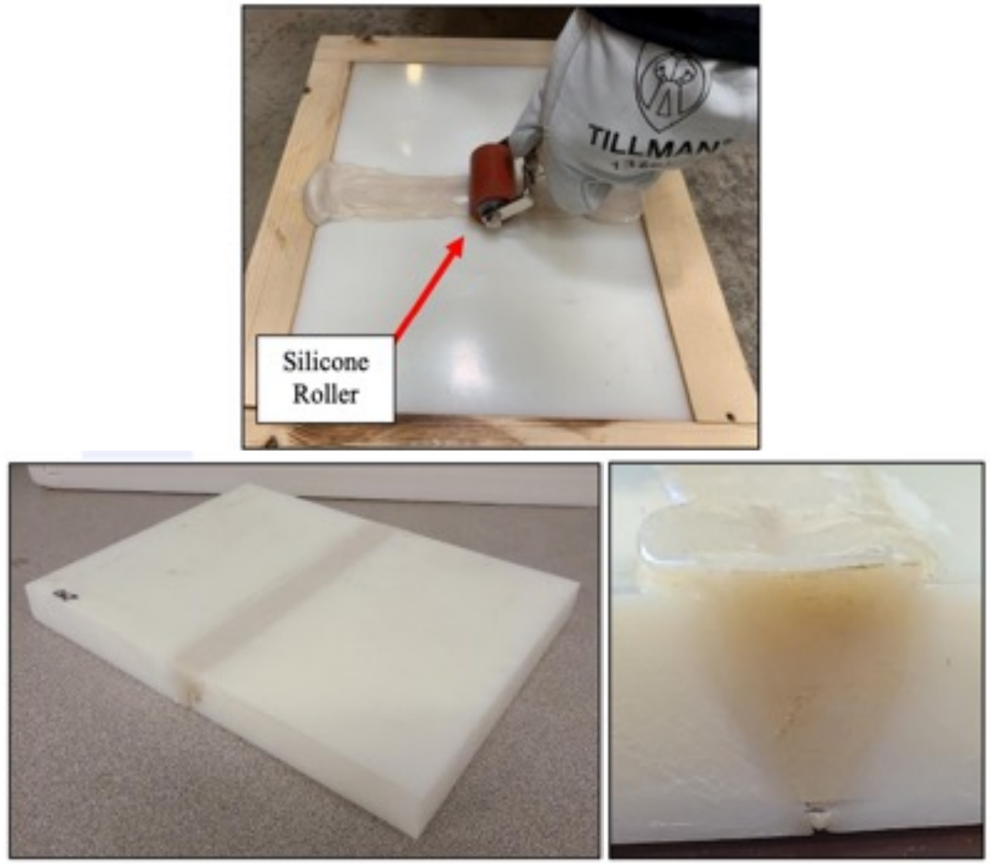
- Additive Manufacturing.
  - Blades and Blade Components.
    - Deposition rate is primary impediment (IMHO).
    - Extensible blade tips (making AM more realistic).
    - TPI engaged with the Labs and Academia on FOA 2960 projects.
    - ”Swarm 3D printing”??
  - Tooling
    - MEGAPRINT
      - Modularity
  - What about Core Materials?
    - NREL leading FOA 2252 project, materials challenge?

photo: The University of Maine

photo: The University of Maine

Looking Forward: Where is Innovation Blooming?

- Additive Manufacturing.
  - Blades and Blade Components.
    - Deposition rate is primary impediment (IMHO).
    - Extensible blade tips (making AM more realistic).
    - TPI engaged with the Labs and Academia on FOA 2960 projects.
    - ”Swarm 3D printing”??
  - Tooling
    - MEGAPRINT
      - Modularity
  - What about Core Materials?
    - NREL leading FOA 2252 project, materials challenge?



Looking Forward: Where is Innovation Blooming?

- Additive Manufacturing.
  - Blades and Blade Components.
    - Deposition rate is primary impediment (IMHO).
    - Extensible blade tips (making AM more realistic).
    - TPI engaged with the Labs and Academia on FOA 2960 projects.
    - ”Swarm 3D printing”??
  - Tooling
    - MEGAPRINT
      - Modularity
  - What about Core Materials?
    - NREL leading FOA 2252 project, materials challenge?

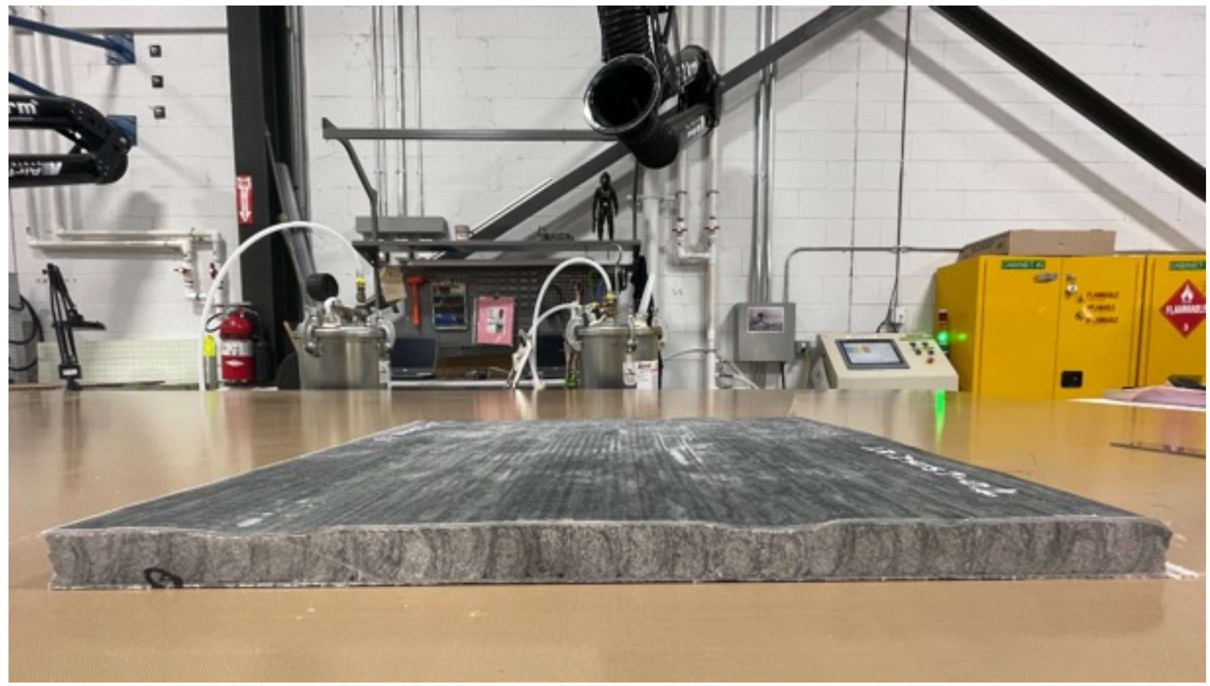
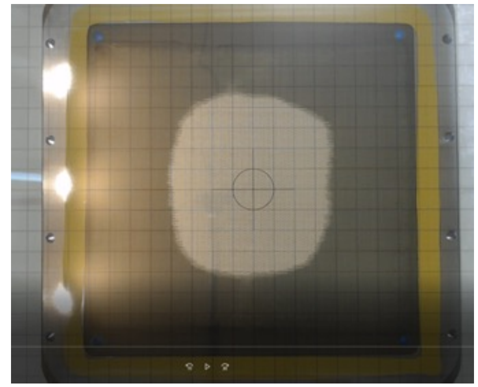
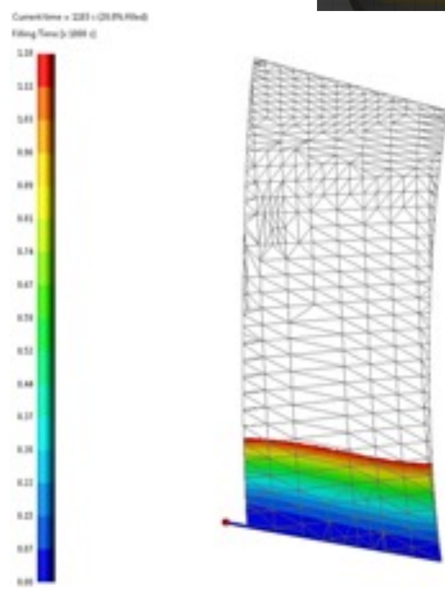


photo: Additive Engineering Solutions & TPI Composites

Manufacturing Control and Quality Improvements: Digital Twins in Manufacturing

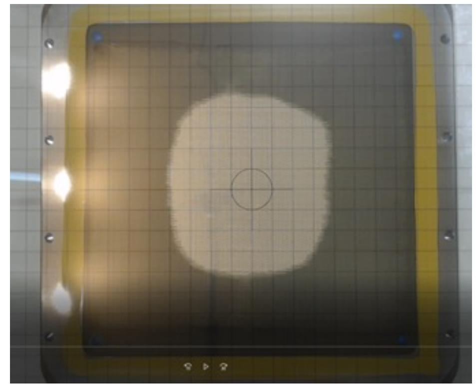
- Infusion Simulation
  - Not a novel concept
  - Computationally Intensive
- *"Machine Learning-based Online Layup and Infusion Process Monitoring and Feedback for Large Wind Blade Manufacturing"* (DOE FOA-2960)
  - Reduced order simulation
    - Coupled with Machine Learning
      - Training model to increase fidelity.
    - Real time use of Vision Systems and AI
      - AI informed control/Identify discrepancies (core gaps, reinf waves, etc).
      - Eliminate infusion defects.
      - Recognize and identify leaks while corrective action is still viable.

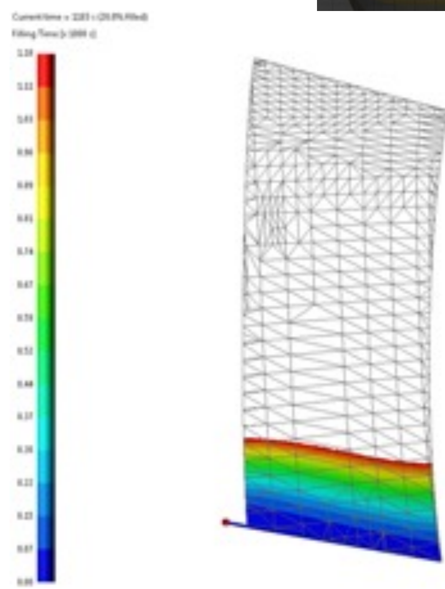


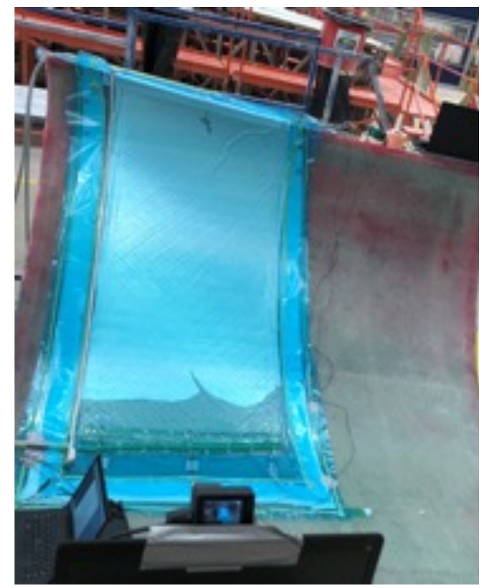


Manufacturing Control and Quality Improvements: Digital Twins in Manufacturing

- Infusion Simulation
  - Not a novel concept
  - Computationally Intensive
- *"Machine Learning-based Online Layup and Infusion Process Monitoring and Feedback for Large Wind Blade Manufacturing"* (DOE FOA-2960)
  - Reduced order simulation
    - Coupled with Machine Learning
      - Training model to increase fidelity.
    - Real time use of Vision Systems and AI
      - AI informed control/Identify discrepancies (core gaps, reinf waves, etc).
      - Eliminate infusion defects.
      - Recognize and identify leaks while corrective action is still viable.

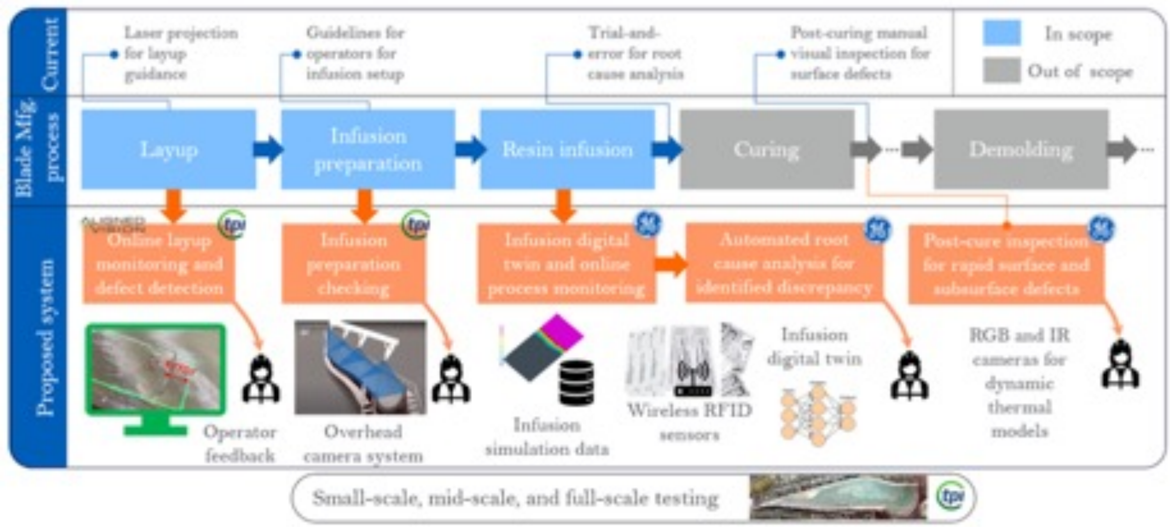






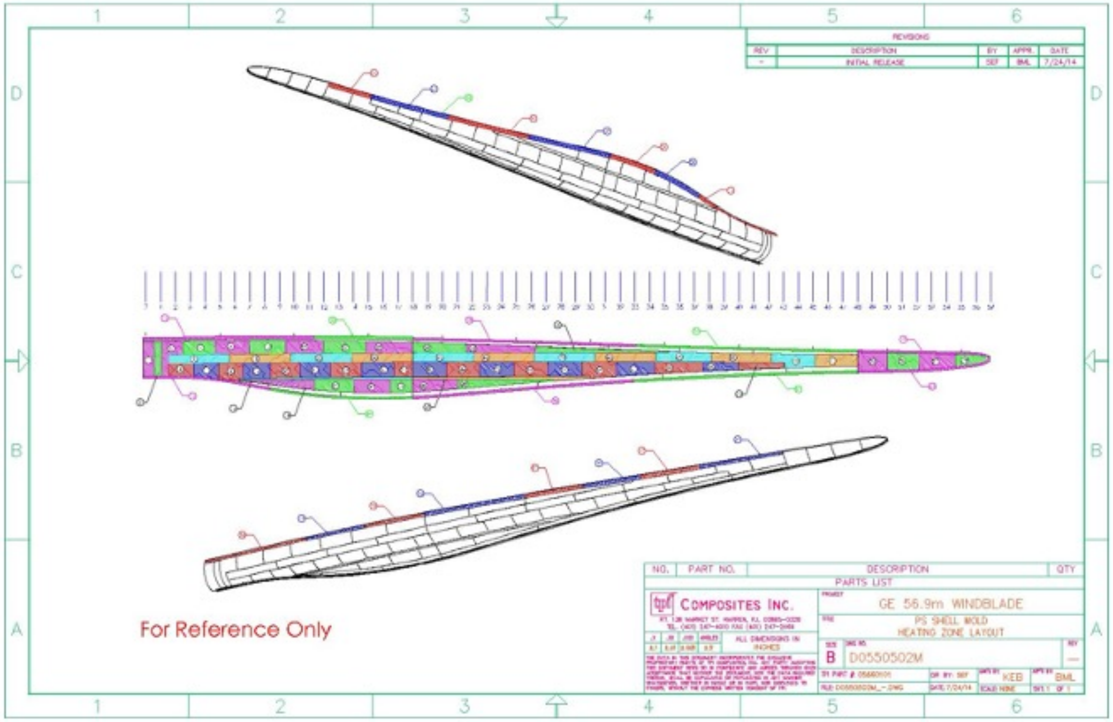
Manufacturing Control and Quality Improvements: Digital Twins in Manufacturing

- Infusion Simulation
  - Not a novel concept
  - Computationally Intensive
- *"Machine Learning-based Online Layup and Infusion Process Monitoring and Feedback for Large Wind Blade Manufacturing"* (DOE FOA-2960)
  - – Reduced order simulation
    - Coupled with Machine Learning.
      - – Training model to increase fidelity.
    - Real time use of Vision Systems and AI.
      - – AI informed control/Identify discrepancies (core gaps, reinf. waves, etc).
      - – Eliminate infusion defects.
      - – Recognize and identify leaks while corrective action is still viable.



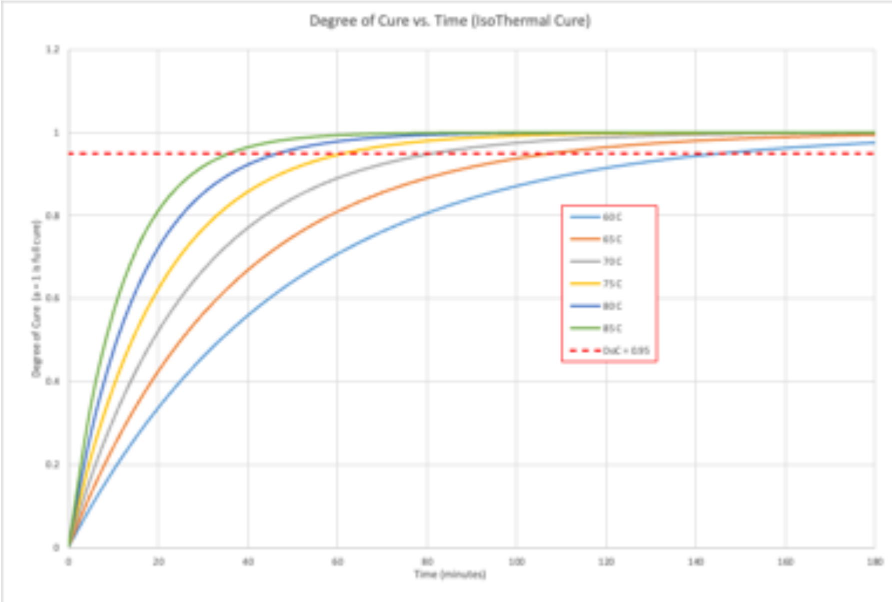
Attacking Cycle-Time and Improving Quality in Resin Processing

- Digital Twins in Processing
  - Typical shell mold > 128 independently controlled zones.
  - Cure profiles traditionally applied as uniform temperature setpoints across the area of infused shells.
  - Root sections more than 75mm thick while tip sections with face sheets < 1mm.
  - Apply cure kinetics models to blade materials, geometry and initial state.
    - Wireless RFID tags (sensors) provide non-intrusive methods to acquire temperature and DoC data.
    - Trained through machine learning with acquired data from multiple experiments.
    - Apply AI methods to direct temperature control.
    - Uniform cure progression and ultimately customer accepted degree of cure (α) across the entire blade.



Attacking Cycle-Time and Improving Quality in Resin Processing

- Digital Twins in Processing
  - Typical shell mold > 128 independently controlled zones.
  - Cure profiles traditionally applied as uniform temperature setpoints across the area of infused shells.
  - Root sections more than 75mm thick while tip sections with face sheets < 1mm.
  - Apply cure kinetics models to blade materials, geometry and initial state.
    - Wireless RFID tags (sensors) provide non-intrusive methods to acquire temperature and DoC data.
    - Trained through machine learning with acquired data from multiple experiments.
    - Apply AI methods to direct temperature control.
    - Uniform cure progression and ultimately customer accepted degree of cure (α) across the entire blade.



$$E = (-2.303R/D)[\mathrm{d}\ \log_{10}\beta/\mathrm{d}(1/T)]$$

$$Z = \beta E e^{E/RT}/RT^2$$

$$\mathrm{k} = Z\exp-(E/RT)$$

$$t_{1/2} = 0.693/\mathrm{k}$$

Attacking Cycle-Time and Improving Quality in Resin Processing

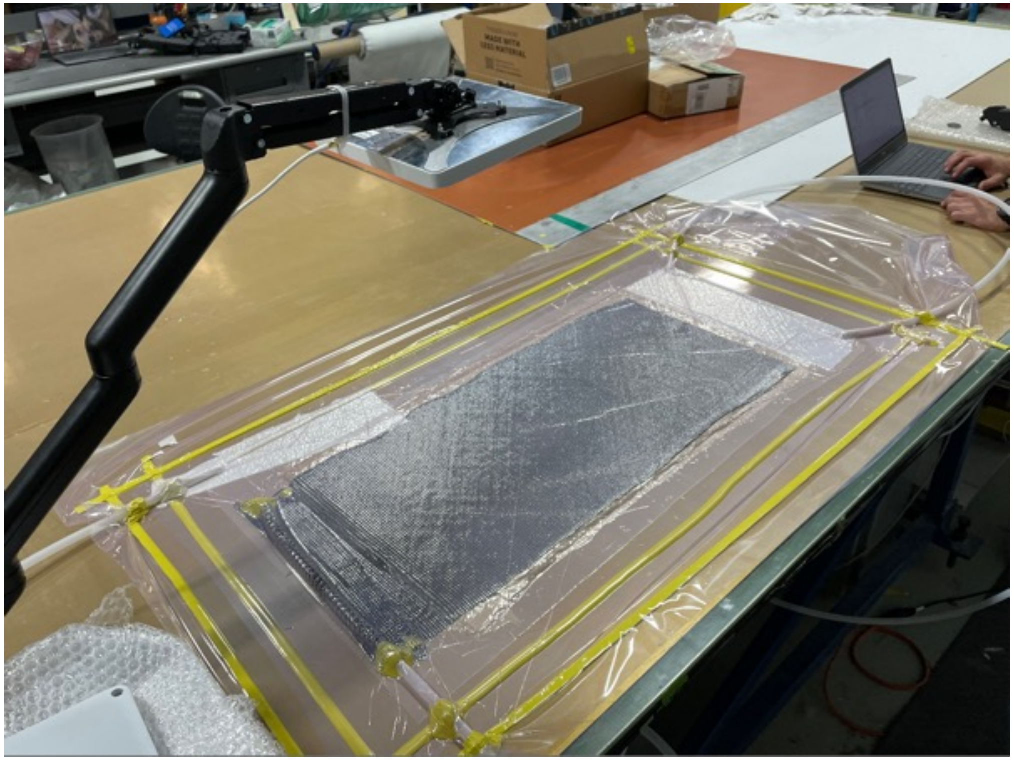
- Digital Twins in Processing
  - Typical shell mold > 128 independently controlled zones.
  - Cure profiles traditionally applied as uniform temperature setpoints across the area of infused shells.
  - Root sections more than 75mm thick while tip sections with face sheets < 1mm.
  - Apply cure kinetics models to blade materials, geometry and initial state.
    - Wireless RFID tags (sensors) provide non-intrusive methods to acquire temperature and DoC data.
    - Trained through machine learning with acquired data from multiple experiments.
    - Apply AI methods to direct temperature control.
    - Uniform cure progression and ultimately customer accepted degree of cure (α) across the entire blade.

Attacking Cycle-Time and Improving Quality in Resin Processing

- Digital Twins in Processing
  - Typical shell mold > 128 independently controlled zones.
  - Cure profiles traditionally applied as uniform temperature setpoints across the area of infused shells.
  - Root sections more than 75mm thick while tip sections with face sheets < 1mm.
  - Apply cure kinetics models to blade materials, geometry and initial state.
    - Wireless RFID tags (sensors) provide non-intrusive methods to acquire temperature and DoC data.
    - Trained through machine learning with acquired data from multiple experiments.
    - Apply AI methods to direct temperature control.
    - Uniform cure progression and ultimately customer accepted degree of cure (α) across the entire blade.

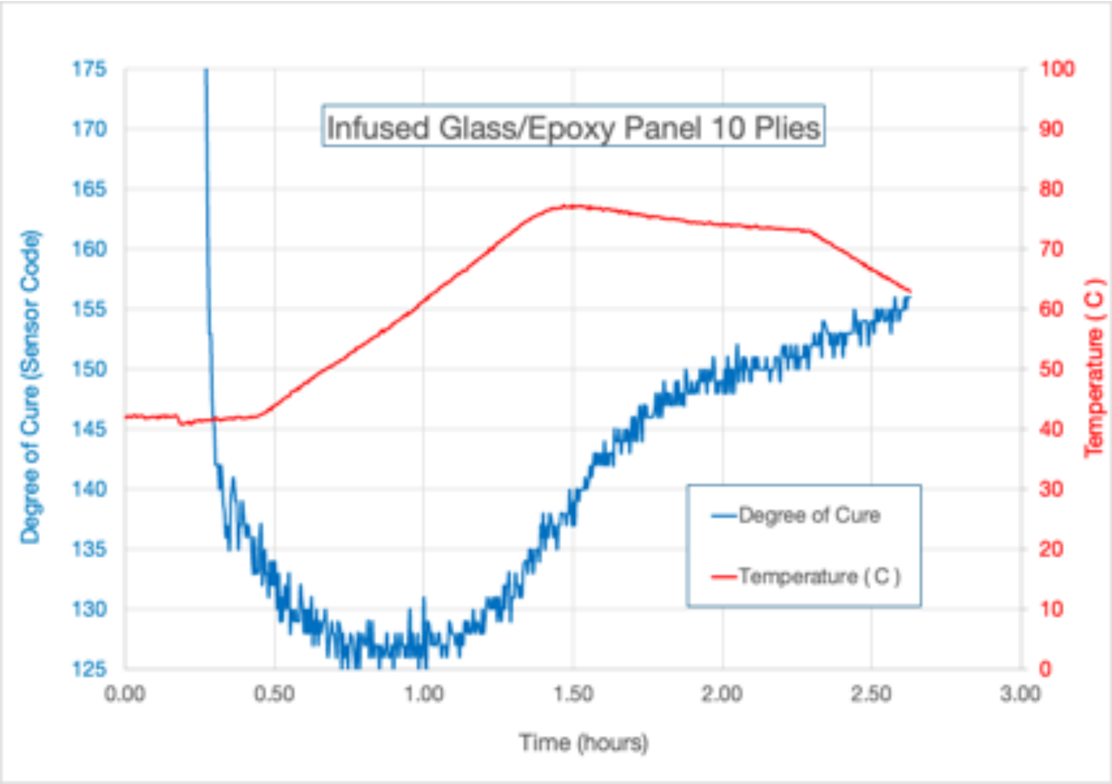
Attacking Cycle-Time and Improving Quality in Resin Processing

- Digital Twins in Processing
  - Typical shell mold > 128 independently controlled zones.
  - Cure profiles traditionally applied as uniform temperature setpoints across the area of infused shells.
  - Root sections more than 75mm thick while tip sections with face sheets < 1mm.
  - Apply cure kinetics models to blade materials, geometry and initial state.
    - Wireless RFID tags (sensors) provide non-intrusive methods to acquire temperature and DoC data.
    - Trained through machine learning with acquired data from multiple experiments.
    - Apply AI methods to direct temperature control.
    - Uniform cure progression and ultimately customer accepted degree of cure (α) across the entire blade.



Attacking Cycle-Time and Improving Quality in Resin Processing

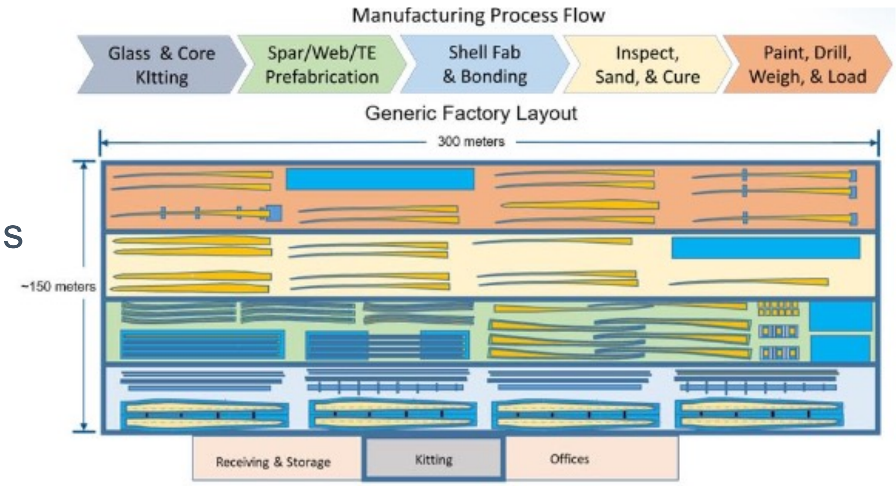
- Digital Twins in Processing
  - Typical shell mold > 128 independently controlled zones.
  - Cure profiles traditionally applied as uniform temperature setpoints across the area of infused shells.
  - Root sections more than 75mm thick while tip sections with face sheets < 1mm.
  - Apply cure kinetics models to blade materials, geometry and initial state.
    - Wireless RFID tags (sensors) provide non-intrusive methods to acquire temperature and DoC data.
    - Trained through machine learning with acquired data from multiple experiments.
    - Apply AI methods to direct temperature control.
    - Uniform cure progression and ultimately customer accepted degree of cure (α) across the entire blade.



Decarbonize & Electrify

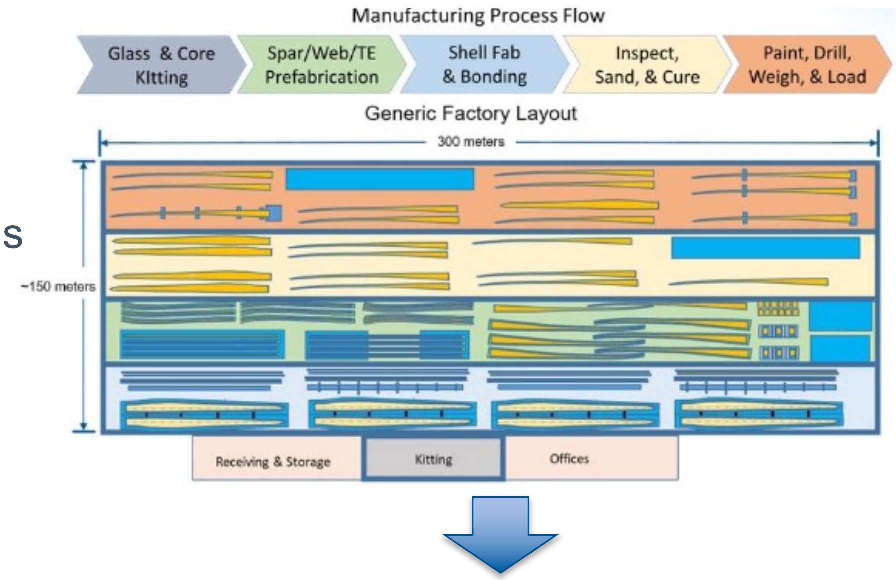
Digital Twins in Manufacturing/Production

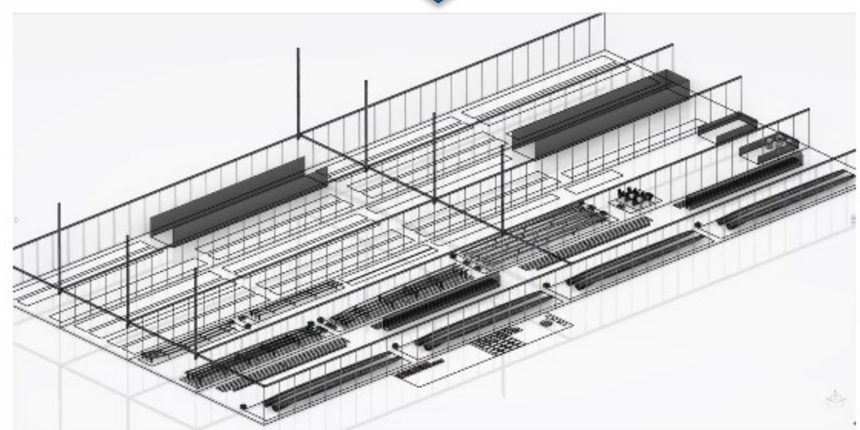
- Multi-work cell environment spread over > 500k ft^2 of workspace.
- Modeling production cycle (workflow process mapping) is common, but output is seldom realized:
  - Cycle-time dependent on of availability of resources:
    - Labor, equipment, fixtures and jigs.
    - Output/capacity is a set of highly couple dependencies.
  - **Discrete Event Simulation** is able to capture these dependencies and predict factory capacity.
    - Identify resource bottlenecks
    - Optimize labor and CAPEX utilization to maximize capacity.
    - Incorporate random perturbations AND impact of automation.
  - Real-time tracking of resources in plant, status of multi-cell progress.
    - Using these inputs to re-shuffle production model and maximize capacity
      - Identify bottlenecks, resolve equipment competition and reduce wait time
      - Increase both CAPEX and labor utilization.
      - RFID tags to monitor equipment location.
      - Machine learning combined with AI methods for constant improvement.



Digital Twins in Manufacturing/Production

- Multi-work cell environment spread over > 500k ft^2 of workspace.
- Modeling production cycle (workflow process mapping) is common, but output is seldom realized:
  - Cycle-time dependent on of availability of resources:
    - Labor, equipment, fixtures and jigs.
    - Output/capacity is a set of highly couple dependencies.
  - **Discrete Event Simulation** is able to capture these dependencies and predict factory capacity.
    - Identify resource bottlenecks
    - Optimize labor and CAPEX utilization to maximize capacity.
    - Incorporate random perturbations AND impact of automation.
  - Real-time tracking of resources in plant, status of multi-cell progress.
    - Using these inputs to re-shuffle production model and maximize capacity
      - Identify bottlenecks, resolve equipment competition and reduce wait time
      - Increase both CAPEX and labor utilization.
      - RFID tags to monitor equipment location.
      - Machine learning combined with AI methods for constant improvement.





Dassault's *DELMIA* 3DExperience factory flow simulation: managing resources.

Finally: A Trained Workforce is REALLY Hard to Build

- Virtual Reality (VR) and Augmented Reality (AR) in Blade Manufacturing.
  - Developing a more capable workforce.
  - Real time resource availability.
    - Work Instructions and visual guides.
    - Cycle-time management.
- Vinci-VR is developing on experiential training using virtual reality.
  - Grant from the Massachusetts Clean Energy Center (Mass CEC).
  - https://www.vinci-vr.com

tpi