Imagination at work.

May 18, 2016

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ASME V&V, Las Vegas 2016
GE Today

Power & Water
Energy Management
Oil & Gas
GE Capital

Healthcare
Aviation
Transportation
Home & Business Solutions

Aligned for growth
GE Global Research

Market-focused R&D
The cornerstone of GE’s commitment to technology

- First U.S. industrial lab
- ~2000 scientists/engineers, nearly two-thirds PhDs
- One of the world’s most diversified industrial research organizations, providing innovative technology for all of GE’s businesses
- 10 locations across the globe:
  - Ann Arbor, Bangalore, Munich, Niskayuna, Shanghai, Rio de Janeiro, ...

GRC Headquarters: Niskayuna, NY
Manufacturing Modeling Lab

- **Casting**
  - Ceramic Core Injection
  - Filling & Solidification
  - Defect Formation – Freckle, porosity, ...
  - Microstructure: nucleation & growth of dendrites
  - Sand casting
  - Die casting
  - Investment casting
  - Spin Casting

- **Joining**
  - Conventional welding
  - Electron-Beam Welding
  - Inertial Friction Welding
  - Brazing
  - Laser/Hybrid Laser Welding

- **Residual Stress/Distortion**
  - Casting, welding/joining, forging, HT machining, LSP, forming...
  - Laser Shock Peening/Shot Peening
  - Ring Rolling
  - Extrusion
  - Sheet Metal Forming
  - Sheet Rolling & Roll Forming
  - Impact of TBC Coating
  - Thermal and Stress Analysis

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There is need to develop guidelines for manufacturing process simulation to ensure that the models are properly calibrated and validated in order to fully benefit from virtual manufacturing.
M&S Maturity Model for Manufacturing
Manufacturing Modeling: Focus Areas

**Design Practice & Governance**
Align Processes to the Digital Thread... new capabilities
- ↓ Cost
- ↓ New Product Introduction cycle time

MRL a critical Step in the Design Process Approval

**Tools: Effective, fast and user friendly**
Improves ease of Design, and affordability for Manufacturability
- ↓ Cost of Quality,
- ↓ Variable Cost Productivity,
- ↑ First Time Yield

MFG tools to be part of Blue Print

**Team: Resources and Skills**
Mfg Engineering skills are scarce, and a bottleneck in design process
- ↑ On Time Delivery,
- ↓ Variable Cost Productivity

Centralized Team - Supply Chain or Eng to “own” it

Significant improvement in the way we work... Enabled by the Digital Thread
M&S Implementation Challenges

Current Mfg **Tools** Immature & Difficult to Use

- Cannot Drive Process Innovations without Validated Tools

**Talent** Depth/Breadth in M&S Methods

- Engineering M&S Analysis-Driven Mindset must be Cultivated

Operations **Processes** Focus on Fire Fighting

- Legacy Culture will Continue to Favor Build It & Bust It

Integrated Org Tool-Talent-Process Required
Maturity Model – Tools (Technology)

M&S to Controls Capability –
Enterprise M&S Driven Decisions
Proactive approach with real time data/control

M&S – Process Optimization –
Operational M&S Assisted decisions with data from actual enterprise

M&S – Process Design support –
Expert M&S analyst driven decisions

No Models –
Empirical trial & error driven decisions

Local Know-how  R&D  Operational  Enterprise

Cannot Drive Process Innovations without Validated M&S Tools
# Maturity Model – Tools (Technology)

<table>
<thead>
<tr>
<th>Primary User of Maturity Model &amp; M&amp;S Tools</th>
<th>Subject Matter Experts</th>
<th>R&amp;D Engineers</th>
<th>R&amp;D and Process Engineers</th>
<th>Enterprise Workforce</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>M&amp;S Tools (Technology)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Process Model Representation</strong></td>
<td>Little or no representational fidelity requirements established for the model geometry, material properties, and process conditions (parameters, initial conditions (IC's), and/or boundary conditions (BC's))</td>
<td>Significant assumptions of the model geometry, material properties, and process conditions (parameters, initial conditions (IC's), and/or boundary conditions (BC's))</td>
<td>Limited assumptions of the model geometry, material properties, and process conditions (parameters, initial conditions (IC's), and/or boundary conditions (BC's))</td>
<td>Real time process and quality assurance data used to refine model assumptions and develop physics based and data driven reduced order models</td>
</tr>
<tr>
<td><strong>Process Physics Fidelity</strong></td>
<td>Empirical data-driven models and/or judgment used to define important manufacturing process parameters in the enterprise</td>
<td>Some physics based models exist for the manufacturing process of interest in the enterprise</td>
<td>Suite of physics based models exist for the manufacturing process of interest in the enterprise</td>
<td>Real time predictions of physics based process performance enable enterprise decisions made within process takt time</td>
</tr>
<tr>
<td><strong>Code/Algorithm/Model Integration</strong></td>
<td>Minimal or no testing of any commercial off the shelf (COTS) or custom software elements with little or no configuration management procedures specified or followed</td>
<td>Source code and algorithms are either COTS software or managed by configuration management procedures with limited comparisons to established algorithm benchmarks</td>
<td>Customized and/or modified algorithms are tested and compared to benchmark data and/or solutions to determine impact on numerical convergence and physics</td>
<td>Integration of M&amp;S algorithms with machine controls and multi-physics data fusion</td>
</tr>
<tr>
<td><strong>Simulation Verification</strong></td>
<td>Modeling assumptions have an unknown effect on the accuracy and/or precision of the numerical process model predictions</td>
<td>Numerical, discretization, and model assumption induced errors qualitatively estimated based on process model input/output for each use case</td>
<td>Numerical, discretization, and model assumption induced errors quantitatively estimated across validation envelope and used to establish M&amp;S best practices</td>
<td>Real time comparison of M&amp;S predictions with process data</td>
</tr>
<tr>
<td><strong>Simulation Validation</strong></td>
<td>Judgment and/or limited experimental manufacturing process data exists to validate process model predictions</td>
<td>Industry standard M&amp;S use cases and benchmark experimental data sets exist and used to calibrate process models at one or more distinct validation points</td>
<td>Data from actual enterprise and/or supplier manufacturing processes used to calibrate process model predictions and establish process validation envelopes</td>
<td>M&amp;S predictions are used to adapt process parameters for real time quality control</td>
</tr>
<tr>
<td><strong>Simulation Uncertainty Quantification</strong></td>
<td>Model prediction uncertainties and sensitivities to key input parameters are not assessed as part of the simulation</td>
<td>Prediction uncertainties inferred from benchmark experimental use case validation data with limited sensitivity studies conducted for key parameters</td>
<td>Prediction uncertainties segregated and propagated by source (geometry, material properties, and process conditions (parameters, initial conditions (IC's), and/or boundary conditions (BC's)) etc.) with detailed sensitivity analyses conducted</td>
<td>Uncertainty and confidence estimates made for all M&amp;S predictions using physics based data-driven reduced order models</td>
</tr>
</tbody>
</table>
Maturity Model - Procedures & Methods

M&S Integrated to Brilliant Enterprise –
Digital twin simulations with real time process control
App type software/automated apps/root cause corrective action

M&S – Process Optimization –
Standard work
Automated set-up/standard evaluation metrics/formal tutorials

M&S – Process Design support –
Experts justification
Informal guidelines/limited case studies

No Models –
Case by case
No guidelines/tutorials

Local Know-how  R&D  Operational  Enterprise

Technology Adoption

Procedures and Methods to Enable non-Expert M&S Use
Guidelines for Manufacturing M&S Applications and Value
# Maturity Model - Procedures & Methods

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</thead>
<tbody>
<tr>
<td>Empirical Trial &amp; Error Driven Decisions</td>
<td>Maturity Level 0</td>
<td>Maturity Level 1</td>
<td>Maturity Level 2</td>
<td>Maturity Level 3</td>
</tr>
<tr>
<td>M&amp;S used for Manufacturing</td>
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<td>M&amp;S Integrated Into</td>
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## M&S Procedures & Methods (Standard Work)

<table>
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<tr>
<th>Physics-Based Model Selection</th>
<th>Little or no criteria exist to aide in the determination of the appropriate level of M&amp;S fidelity required for process modeling</th>
<th>Analyst expert knowledge used to determine the appropriate fidelity required for physics based M&amp;S of manufacturing process design problems</th>
<th>Decision criteria to aide with the matching of physics based M&amp;S fidelity to families of manufacturing process design problems have been developed as standard work</th>
<th>Digital twin simulations used to establish decision criteria for real time process control what-ifs</th>
</tr>
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<tbody>
<tr>
<td>Analysis Set-Up &amp; Execution</td>
<td>No analysis or simulations performed ad hoc using software manuals and software tutorials on a case by case basis by M&amp;S non expert users</td>
<td>Informal guidelines developed by M&amp;S expert analysts used to guide manually intensive analysis set-up and execution</td>
<td>Standard work defined that enables non-expert users to apply M&amp;S to problems with automated analysis set-up scripts and/or interfaces streamline model development</td>
<td>App type software enables enterprise workforce to apply physics based M&amp;S as a tool to solve production problems</td>
</tr>
<tr>
<td>Result Interpretation</td>
<td>Judgement and/or subject matter expert knowledge used to interpret M&amp;S results and determine if solutions are correct</td>
<td>Analyst expert knowledge used to determine numerical and physical validity of predictions based on M&amp;S analyses of similar manufacturing processes</td>
<td>Standard metrics used to evaluate M&amp;S results and determine the validity of predictions based on best practices and lessons learned of similar processes</td>
<td>Automated apps used to compare M&amp;S predictions with real time process data and provide closed loop feedback to process</td>
</tr>
<tr>
<td>Application Tutorial Development</td>
<td>Applications for M&amp;S software and associated tutorials are limited to those that came with the COTS M&amp;S software</td>
<td>Limited enterprise case studies documented to illustrate how physics based M&amp;S software has been applied to solve example manufacturing process problems</td>
<td>Numerous enterprise case studies compiled into formal tutorials to illustrate how to apply physics based M&amp;S tools to solve a variety of manufacturing process problems</td>
<td>Tutorials describe applications of physics based M&amp;S to assist with enterprise root cause corrective action (RCCA) activities to eliminate manufacturing defects</td>
</tr>
</tbody>
</table>
Maturity Model: a Tool to Help Develop Business Roadmaps

M&S Career Path with Control Titles -
- M&S skill set criteria for key leadership positions/development
- Assist manufacturing management activities
- Physical to virtual environment

M&S - Dedicated Department -
- Responsible M&S Ownership with necessary skills
- Support NPIs/Product & process quality control

M&S - R&D Pilot Areas -
- Individual experts on projects/Evaluate NPIs
- Validated data for production user cases

No Function -
- Self-trained/Limited application/Limited ownership

Capability Maturity Level
- Local Know-how
- R&D
- Operational
- Enterprise

Tribal Knowledge
- Optimized
- Integrated

Technology Adoption
Manufacturing M&S Skill Set Competencies need to be Defined

Engineering M&S Analysis-Driven Mindset must be Cultivated

Workforce M&S Learning Curve will Follow S-Curve Trajectory
Discussion and Conclusions

CMMI Framework Leveraged to Define Thread Focus Areas

Maturity Level Themes Refined to Drive Org Transformation

Sub-Thread Focus Refined to Accelerate Org M&S Adoption

Work with V&V Committee to Partner with Businesses and Academia to benchmark capabilities