Sustainable Manufacturing via Multi-Scale Physics-Based Modeling

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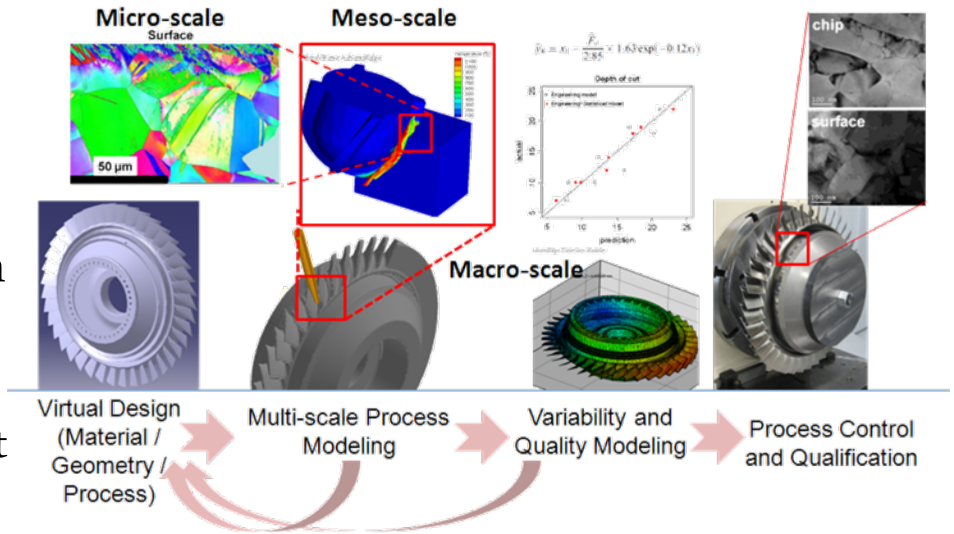
Project Objective

- What are we trying to do?
  - Develop and demonstrate a new **manufacturing-informed design paradigm** to dramatically improve manufacturing productivity, quality, and costs of machined components
- What is the problem?
  - Current machining processes and cutting tool designs are slow and too conservative, leading to high costs and significant waste
  - Currently, design teams are "*manufacturing-aware*," but not necessarily "*manufacturing-informed*"
  - Performance, Cost and Quality problems are found too late in the Product Development Process
- Why is it Difficult?
  - Lack of sufficient fundamental understanding of process physics
  - Lack of physics-based process design and optimization tools for finish and semi-finish operations
  - High computational costs of modeling at multiple length and time scales for process optimization
  - Statistical variability of tooling, equipment and materials

Technical Innovation

- **State-of-the-art**
  - "*Manufacturing aware*" part and process design – No knowledge of process outcomes (cost, quality, performance) until manufacturing trials
  - Long and slow trial-and-error design of machining processes and cutting tools
  - Resulting manufacturing processes and cutting tool designs are conservative – unnecessarily slow, sub-optimal and expensive
- **Innovation**
  - **Multi-scale Physics-based Modeling** can provide detailed knowledge of process outcomes before manufacturing trials
  - **Physics-based Optimization** can squeeze significant productivity from state-of-the-art machining processes
  - **Reduce** (rough and finish) **machining costs and cycle times**, while **extending tool life** and maintaining **component performance**
- **Numerical simulation / optimization**
  - Very challenging but preferred to trial-and-error
  - Over 20 years of continuous development and software deployment



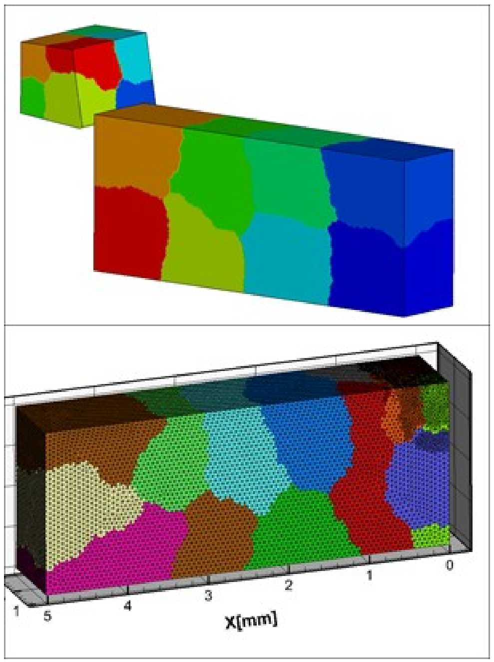
Technical Innovation

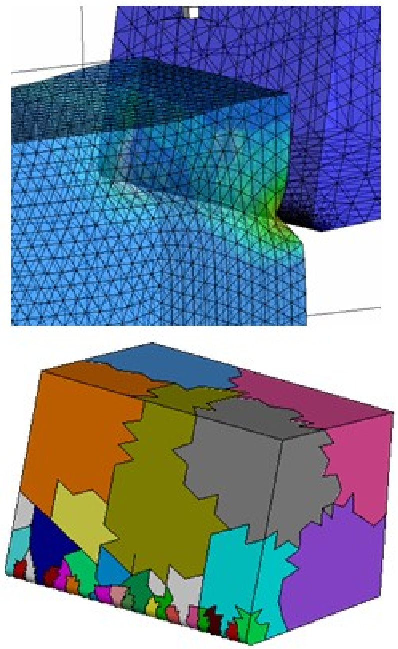
- **Distributed or hybrid parallelization of AdvantEdge**
  - Shortening time-to-solution and project size demands of customer are increasing
  - Employ multiple computers connected with a fast interconnect
    - Substantial change in programming paradigm; data-dependencies are explicit
    - Method has been exploited in other field of simulation for decades
    - Hardware: MPI, Intel Haswell CPUs 36 core, Infiniband (tested extensively)
  - Allows for larger problems to be made tractable than present technology
  - Faster assessment of accuracy via rapid mesh resolution studies
  - **Cost:** implementation requires substantial development effort

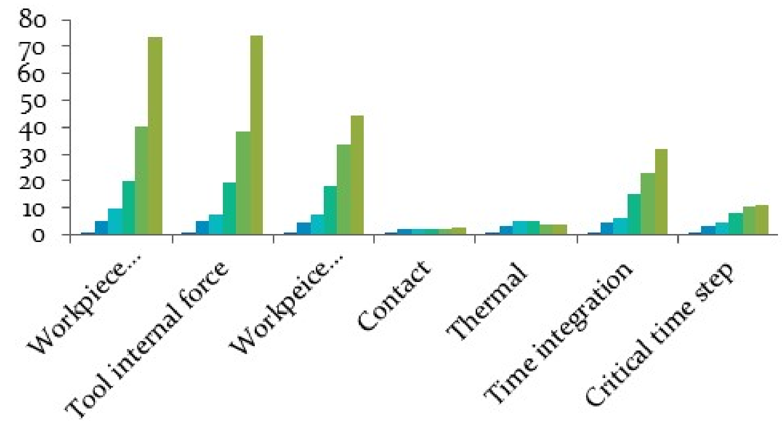
- **CAM system integration with Production Module and advanced optimization algorithm to recommend optimization values**
  - Seamless bi-directional integration with CAM system
  - Allows physics-based optimized manufacturing data to be centrally managed in Product Lifecycle management workflow
  - Converts decision making know-how in physics-based optimization domain into software system to benefit expanding end user bases
  - Allows physics-based toolpath optimization to be automated from CAM to Production Module to CAM

Technical Approach

- **Distributed parallelization of AdvantEdge**
  - Domain decomposition (ParMETIS, DSDE), parallel mesh adaptation , parallel contact algorithm based on one-sided communication



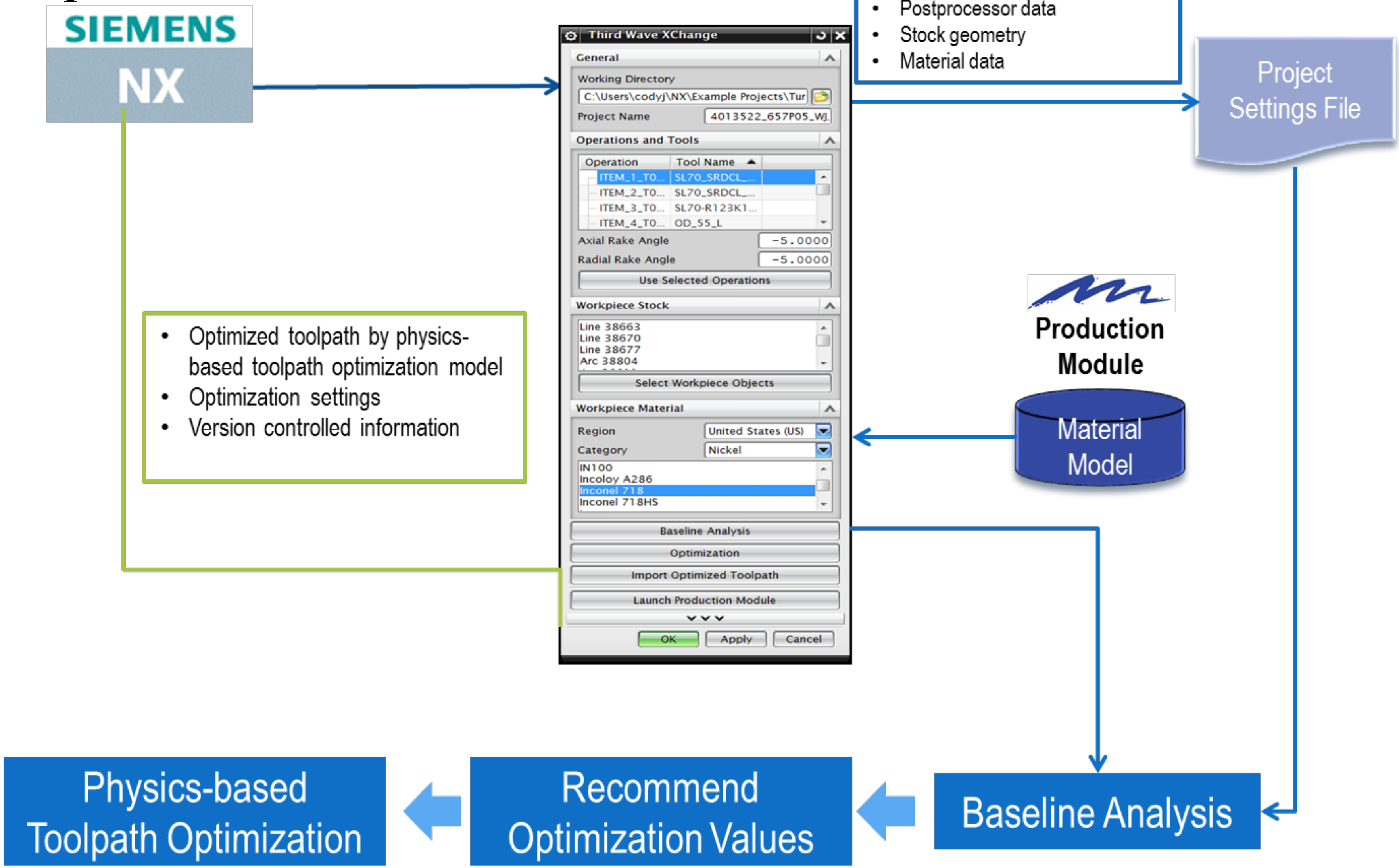




- **Algorithmic challenges**
  - Parallel mesh adaptation strategy and implementation
  - Parallel surface contact algorithms and efficient collision detection
  - Domain decomposition / load-balancing must be driven by the physics simulated
- **First generation distributed solver is meeting most objectives; needs work**

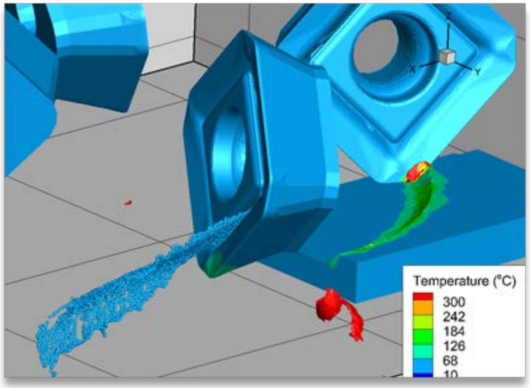
Technical Approach

- **CAM Integration and Recommended Optimization Values**

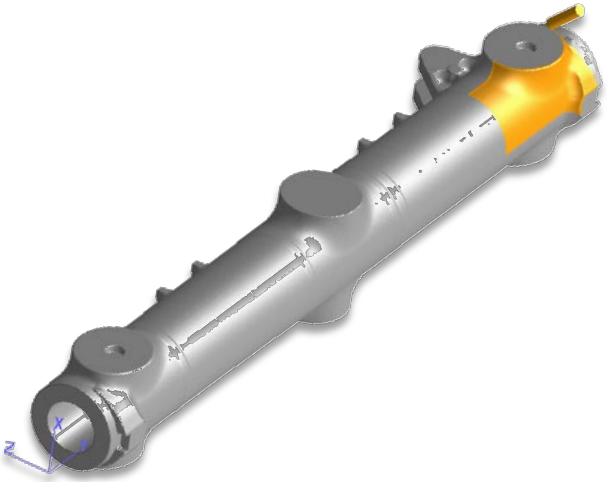


Transition and Deployment

- Technology will be incorporated into existing commercial products; transition has begun
- Cutting Tool Manufacturers Care
  - **Who**: Kennametal, Ceratizit, Ingersoll, Sandvik, Allied Tools
  - **Why**: Improve cutting tool designs - specifically coolant delivery and tool life–related improvements, faster tool design iterations
- Aerospace, Auto, Medical, O&G manufacturers
  - Jet Engine: GE, Pratt & Whitney
  - Airframe: Boeing, GKN Aerospace, NexTech
  - Auto: GM, Ford
  - **Why**: Higher tool life, reduced cycle times, reduced costs, reduced energy consumption, effective coolant usage, improved final microstructure properties and performance, accelerated insertion of new materials

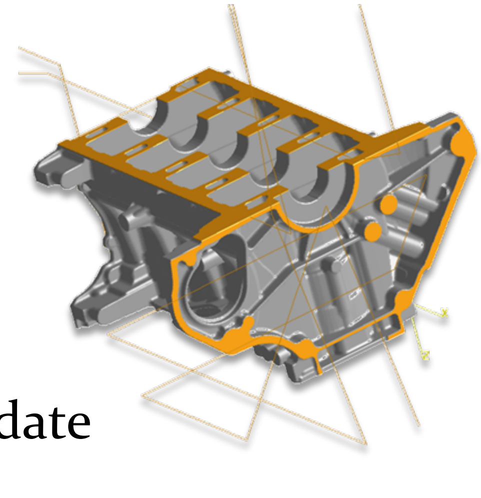


Cutting Tool Manufacturers



Aerospace Component

Transition and Deployment



- Heavy Equipment (Caterpillar)
- Medical Implants (e.g. DePuy Synthes)
- Oil & Gas and Power Systems (GE)
- Technology Sustainment Strategy
  - Partner with early adopters and market leaders to interface and integrate into their systems and validate the business case
  - Partner with industry leading PLM system developer to speed up deployment and collaborate in the early stage of development
- *Transition results to date*
  - Core technology from DoE program resulted in the sale of 40 software licenses across 20 companies in 2015
  - Sales were primarily to automotive and aerospace companies interested in efficient manufacturing

Measure of Success

- **Impact and Metrics**
  - **Metrics (fundamental level)**: Correlation (error %) with experimental data for Forces, Torque, & Microstructure
  - **Metrics (tool-path level)**: Achievement of 50% reduction in machining cycle time on representative components

- **Energy and Economic Impact Estimates**
  - Achieve **50 percent reduction in machine tool *tare* energy and water consumption** in machining via reduced cycle times, coolant and tooling consumption.
  - Achieve a **50 percent reduction in cycle times and energy consumption** for machining.
  - Save over **4.1 trillion BTUs per year** and **7.2 million metric tons of CO_2-equivalent per year** for machining processes.
  - Estimated savings of **$1.14 billion in tooling** costs, reduction of **$24 billion in cutting fluid** costs

Project Management & Budget

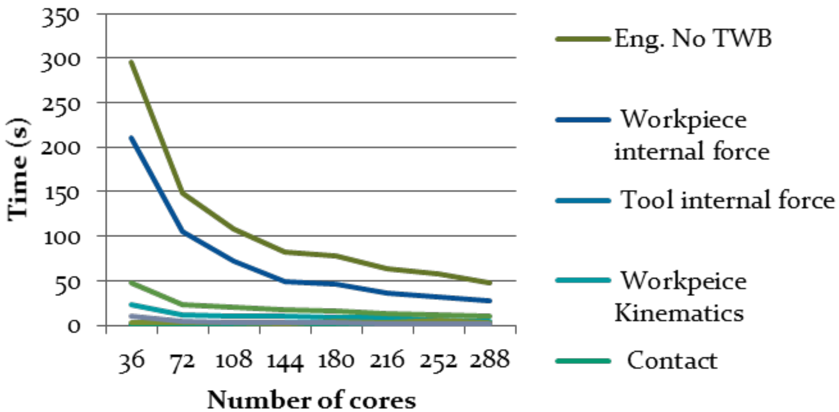
- Project Duration : 36 months
- Project task and key milestone schedule
  - Project Plan has Qualitative and Quantitative Milestones
  - Comparison against experiments (validation metrics)
- Have met all the go / no-go gates and milestones

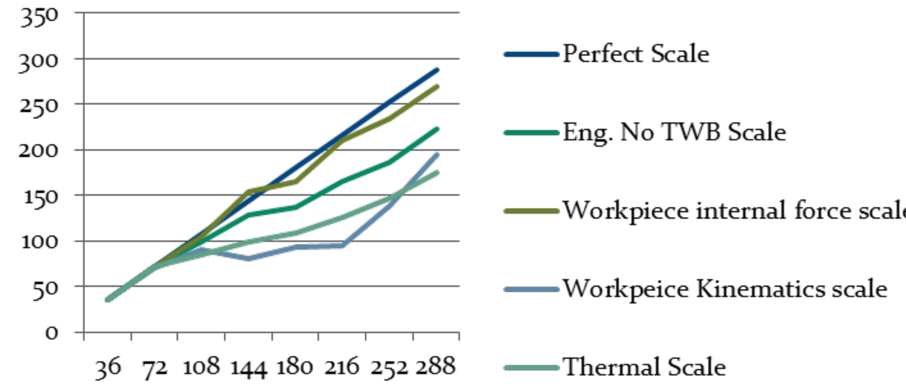
Number	Go / No-go Description	Verification Method	Planned Completion Date
1	Coolant model implementation	Simulate 27 turning cases, achieve 90% completion success rate	End of Budget Year 1
2	Tool wear model prediction	Simulate 18 conditions, achieve 90% success rate of completion	End of Budget Year 2
3	Cutting force prediction	Predicted and measured forces within 30% agreement	End of Budget Year 2

Total Project Budget	
DOE Investment	$4,069,880
Cost Share	$964,719
Project Total	$5,034,599

Results and Accomplishments

- Ported AdvantEdge technology to high performance computing on multi-core, distributed memory systems
  - Work is on-going; building multi-level parallelization (decoupled approach)





- Seamless bi-directional CAM integration
  - Deployed at several customers sites
  - Improved: productivity, traceability, manufacturing data management, process of design change, and optimization turnaround cycle time
- Optimization values recommendation “Expert System”
  - Tested and verified with 200+ customer toolpath programs
  - Advanced algorithm and enhanced workflow significantly improve the efficiency and effectiveness of using physics-based toolpath optimization