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DMDII FINAL PROJECT REPORT

From Art-to-Part: Multidisciplinary Virtual Toolset for Laser Power-bed Fusion Additive Manufacturing and Multi-Step Post Processing Certification

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I. EXECUTIVE SUMMARY

Powder-bed Fusion Additive Manufacturing processes (PBFAM) combine precision powder bed formation for materials deposition with high resolution micro-welding for direct materials consolidation. It enables on-demand bespoke manufacturing and radically disruptive supply chains. Structured methods to mature and certify PBFAM are in their infancy meaning that numerous process iterations are required to achieve the requisite form and fit tolerances, surface finish, and material integrity. Thermal distortion, feature dependent surface roughness, shrinkage, cracking, and porosity are known artifacts in the PBFAM process. While prior efforts have focused on optimizing the PBFAM process, this team took a holistic look at optimizing a substantial subset of the manufacturing process chain used to take a design from concept to the final part. This includes the analysis and optimization of part geometry and material state through PBFAM, heat treatments and bulk machining.

Through this project, GE Global Research worked with the University of Cincinnati, the University of Illinois at Urbana-Champaign, and TechSolve and developed an integrated framework and underlying toolsets to accelerate the process certification A series of analytical and process optimization tools were developed including: 1) model-based producibility tool for PBFAM and machining; 2) PBFAM scan path optimization to ensure high material integrity; 3) prediction of thermally induced distortion; 4) part compensation for distortion and machining processes; 5) machining consideration and evaluation. A summary of the program is shown in Figure 1.

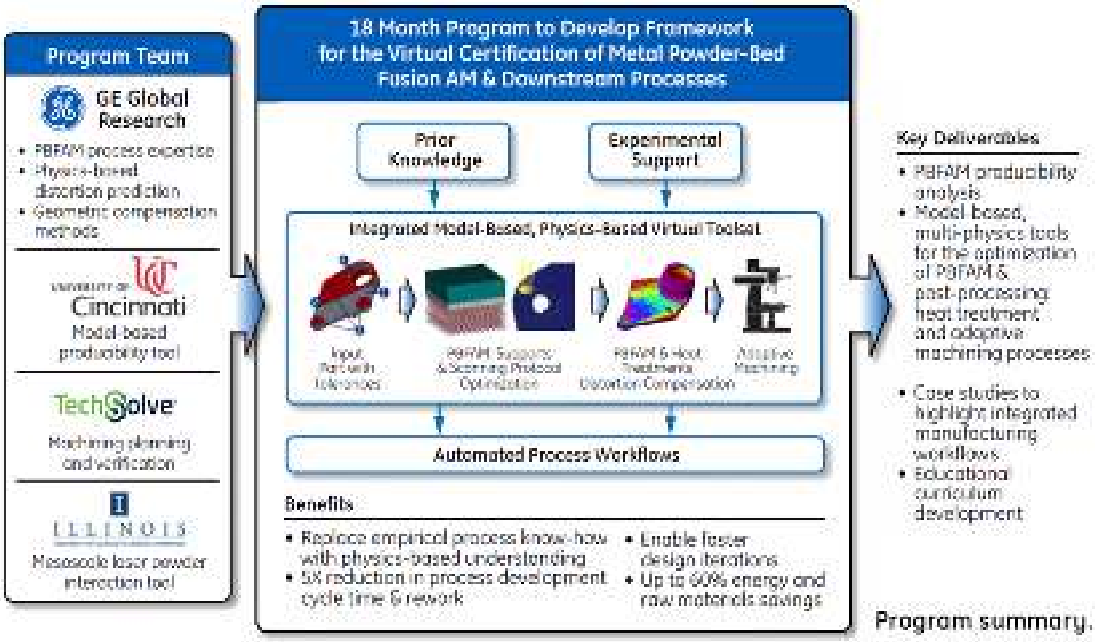


Figure 1. Program Summary

The proposed virtual process allows real-time pre-processing to check geometry features and automatically add support structure, and also early consideration of post-processing. It treats the part design, PBFAM process, heat treatment processes, and machining as an integrated value stream, therefore, avoiding significant rework due to the sequential natural of the physical process. Meanwhile, the feedback from the pre-processing tool, distortion prediction, and machining verification provides a clear objective to guide part redesign. By utilizing the developed virtual toolset, more than 60% of the physical iteration can be moved to the virtual process. This leads to a 60 to 70% savings in both energy and raw materials arising from the reduction in process iterations. With the automatic flow and the assistance of high performance computing, a more than 3 times reduction on the cycle time is achieved due to much less physical iterations, inspections, and verification. Through the demonstration of a designed revolving geometry, the mean distortion was reduced more than 70% through 2 numerical iterations. This is also applied to a complex Bracket part where the mean distortion was controlled to less than 0.03 mm. Each individual tool also serves its unequal capabilities for producibility, support structure design, distortion and residual stress prediction, compensation for distortion and machining, and post-processing tolerances. The independency of each tool also provides tremendous flexibility to customers to focus on one or two problematic areas of most concern. One outcome of this work is that it has been awarded the “Best Paper” in 2018 Manufacturing Science and Engineering Conference.

The developed toolset allows the burgeoning AM industry to broadly adopt modeling and simulation technologies, thus accelerating and standardizing their process certification methods. The team envisions that this will unlock tremendous value for small and medium size enterprises (SME) and also Original Equipment Manufacturers (OEM) to turn design to product in weeks instead of months with significant cost savings.

II. PROJECT REVIEW

The conventional method to develop the LPBFAM progress follows the operation sequences. Figure 2 shows the current procedures that are involved in the LPBFAM process. The initial CAD model is pre-processed by machine-specific software to generate the process parameters and scan paths based on the experiences from the operation engineering. Once the part is printed, heat treatment procedures are carried out to reduce the residual stress and finally tune the properties depending on the applications. The part is then removed from the plate to perform the final machining to achieve the final geometrical tolerances. Under current operations, any defects occurring during this process chain will lead to revisit or rework of the previous process. Numerical physical iterations are expected to achieve the right geometry tolerances with acceptable defects. This is extremely time-consuming and costly, in particular, at the end of the process. For example, during the machining stage, the distortion during printing and heat treatment processes may result to insufficient machining stock. To solve this problem without the pre-knowledge of distortion, additional machining stock has to be examined through experiments, added to the original CAD and re-evaluated through the entire process.

Figure 2. Current sequence of operations

GE Global Research (GEGR) worked with the University of Cincinnati (UC), the University of Illinois at Urbana-Champaign (UIUC), and TechSolve to develop a multidisciplinary toolset to enable a virtual workflow as shown in Figure 3. By extensive use of virtual tools, the team anticipates reducing the overall development time from 10–18 weeks to 2–3 weeks.

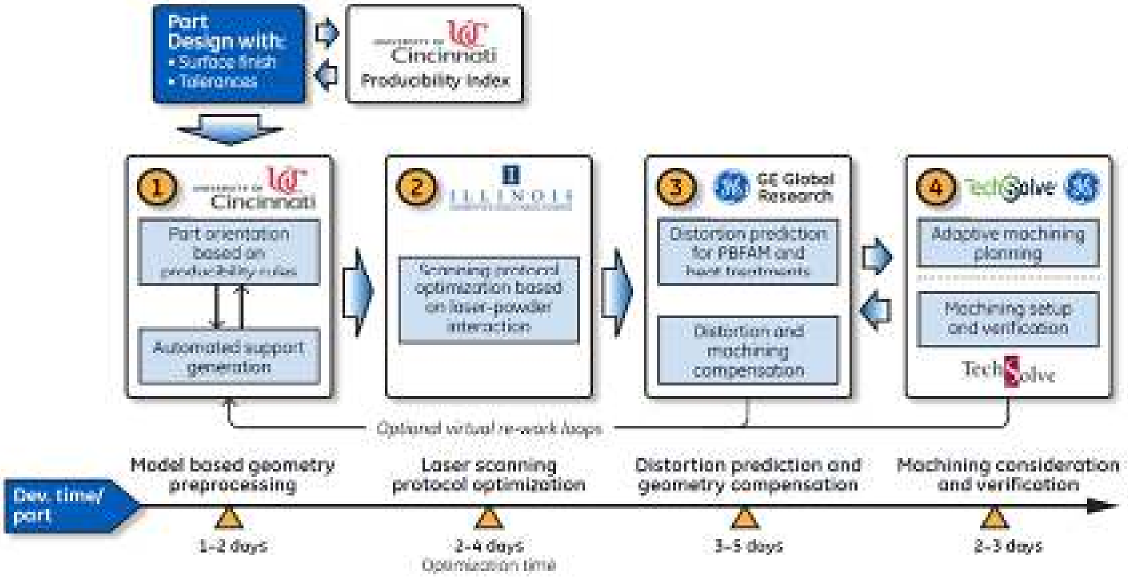


Figure 3. Proposed methodology making extensive use of virtual tools to reduce development time from 10–18 weeks to 2–3 weeks.

The workflow consists of 4 major modules under 5 Tasks. Modules 1, 2, and 4 are executed under Tasks 1, 2 and 5, respectively. Module 3 is split to Tasks 3 and 4 to focus on distortion prediction and geometry compensation, respectively:

Module 1: Model-based pre-processing tool to orient part with producibility index ranking and automatically generate support structures;

Module 2: Laser scanning protocol optimization tool to explore AM machine parameter space to determine optimal machine settings based on a mesoscale laser-powder interaction model;

Module 3: Distortion prediction and geometry compensation tools to account for machining stocks and mitigate distortion during PBFAM and heat treatment processes based on Finite Element Analysis (FEA);

Module 4: Machining consideration and verification process to evaluate design for adaptive machining planning and final tolerance verification.

When a part has finished the with design phase for manufacturing, a pre-processing tool will be used to check the producibility ranking via the Producibility Index (PI). If the PI is low, the part can be sent back for redesign until the PI is high. The confirmed design then enters the main virtual loop for processing. Module 1 automatically generates and optimize support structures based on the producibility rules. Module 2 takes critical features from the design and perform mesoscale laser-powder interaction simulations to ensure materials integrity with good surface finish. Module 3 uses the laser scanning protocol that is optimized in Module 2 to first predict distortion and residual stress during the PBFAM process; second, carry the distortion and residual stress and perform simulation for subset heat treatment processes one by one from stress relief, to HIP, to solution heat treatment; and third, perform geometry compensation for distortion as well as machining stocks that are provided in Module 4. If the distortion is severe and/or cracking occurs, the part will be redirected to Module 1 for support structure redesign to help on reducing stresses. Module 4 determines the machining planning based on the distortion predicted in Module 3 and also perform the final machining verification. If the machining procedure cannot make the part adhere to the part geometric dimensioning and tolerancing (GD&T) requirements or significant materials removal is required, modification on machining compensation can be performed in Module 3 to provide the appropriate corrected part geometry. In the case that iterations between Module 3 and Module 4 cannot satisfy the tolerance requirement, a rework loop can be performed in Module 1 to do further adjustment. The detailed methodology and main results for each module are described below.

The modules are connected through passively passing data between models. The original design of the part, CAD file, is the input for the preprocessing tool. The tool automatically evaluates the geometry and outputs the PI value based on individual weighting factor that user provides. If support structure is required for the orientation, the tool will also combine the support structures with the original CAD file to create a new geometry for machine to build. The local geometry feature from Module 1 needs to be extracted by the user to import to module 2, which focuses on melt pool simulation. Both laser power and speed will be optimized in the program to achieve the criteria that is defined by the user, in this program, the melt pool depth. The entire geometry and variations of the process parameters are imported to module 3 to carry out the FE simulation to address the residual stress and distortion. The compensation tool will compensate the geometry based on the predicted distortion. Iterations may be required to ensure that the distortion is within defined tolerance. If machine procedure is required, the machining stock can be added either to the original CAD before the pre-processing or to the compensated geometry where an extra function has been developed to increase dimensions of the CAD file.

Technical details, case studies, validation and applications can be found in the final presentation provided to DMDII. The exact locations are listed in Appendix.

Module 1: Model-Based Pre-processing

UC led the effort to develop a model-based pre-processing tool. To capture the producibility rules, UC performed an extensive literature study and developed a set of design rules that combined with the practical information from GE to come up with a consolidated knowledge base for producibility. For example, an offset based contour analysis algorithm was developed to detect critically thin sections and small openings.

An isocline-based algorithm for the generation of support structures was developed in this program. The surfaces of the part model were first discretized into fine set of points and normal information was computed at each point. The points that have a normal larger than a certain angle with the build axis are joined sequentially to form a region constructed by isoclines. A rule-based surface was created joining the boundary isocline with projected curve to form the support. A voxel-based support optimization routine was implemented to determine the volume of supports. By simulating the voxel size to be the tool diameter of the tool used for support removal, support removal feasibility can be analyzed by traversing along the six cube face directions towards the outer boundary of the part.

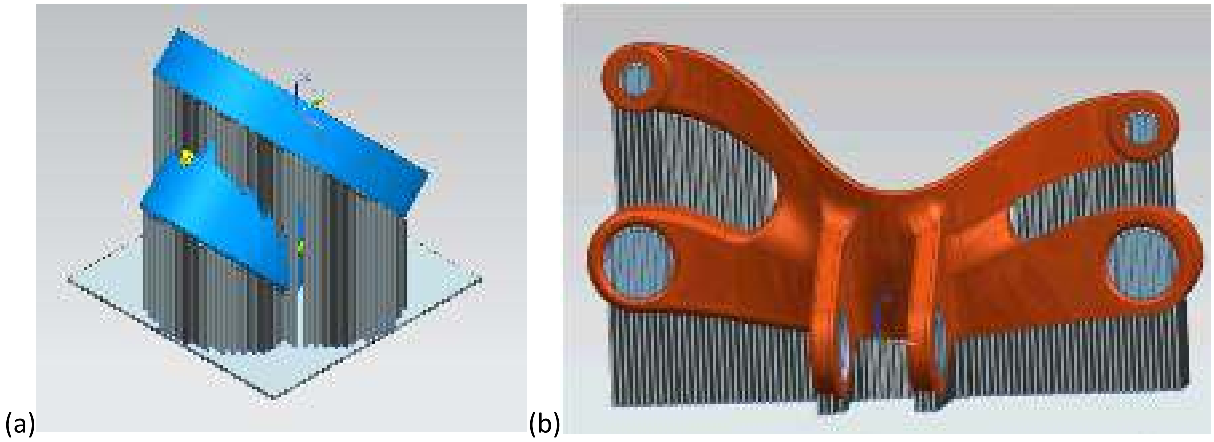


Figure 4. Generated supports for a) revolving part and b) Designed part

Since orientation determines the support design, a consolidated optimization model, as shown in Figure 5, was be developed to identify the optimum part build orientation that reduces the overall part build time while ensuring optimal use of support structures. The oriented part with generated support structure was then exported both for the AM machine to build and for physics-based numerical models to run analysis. An index calculation scheme was developed for producibility comparison of designs. The concept of the PI includes the following factors:1) total number of sharp corners, 2) number of critically small holes/opening, 3) thin regions, 4) thin-to-thick/thick-to-thin transitions, 5) surface area contacting support, 6) volume of support required, 7) height of the part, and 8) volume of the part. The selection of the factors is based on the literature research and factory experiences with GE. This list covers the most common features that AM process may has difficulties to process with or produce defects. Different weighting factors were added to each element to form the mathematical equation. An increase in the index ensures the design evolution for producibility.

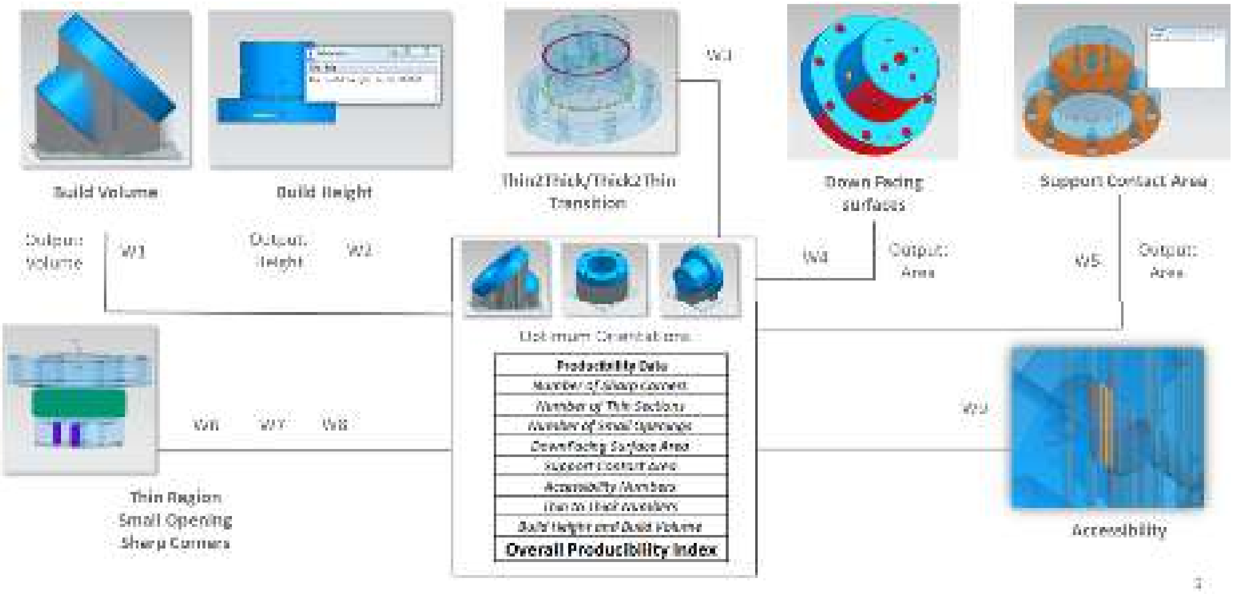


Figure 5. Producibility Index for pre-processing optimization

The pre-processing tool was used to evaluate the orientations for a revolving geometry with 7 orientations. Since the weighting factor is based on users interests, for this case study, each factor was evenly weighted. The detailed numbers for orientation 0, 10 and 180 were also shown in Figure 6. Orientation 180 yields the largest build volume and orientation 10 has the most down facing surface. The PI number is shown in Figure 6, which suggests that orientation 0 has the balances for making a quality build.

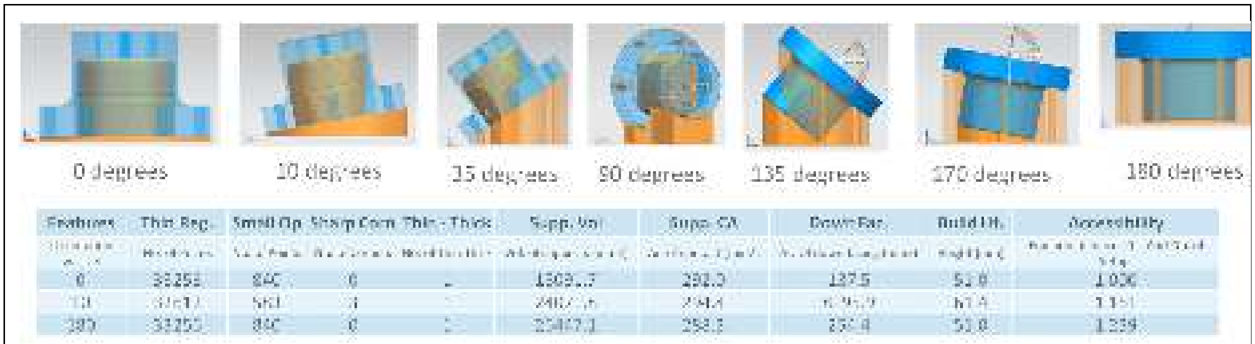


Figure 6. Evaluation of the producibliity index based on part orientation

To qualitatively check the build quality, 5 orientations (except 10 and 170 degrees in the 7 evaluated orientations) were built, shown in Figure 7. Orientation 0 has the least deformation based on both experimental measurements and numerical model prediction. Note that, the weighting factor that will significantly affect the PI number, since it can total remove the evaluated factors by assigning a zero value. The intention here is to provide the maximum flexibility for users to evaluate the geometry.

Orientations w.r.t. X	PI Higher is better
0	0.83
10	0.61
35	0.42
90	0.37
135	0.37
170	0.61
180	0.60

Figure 7. Caculated PI and the printed parts with different orientations

Module 2: Laser Scanning Protocol Optimization

UIUC led the effort to optimize laser scanning protocol for the PBFAM process. Without deep customization, parts normally were printed with one set of laser parameters. For example, the sample laser power and speed were used for bulk materials and also for the overhang region. Due to the different thermal characteristic, large differences were exhibits in the melt pool size, which also reflects the difference in the final microstructure and surface finishing. In order to achieve similar materials behavior, different laser power and speed should be signed based on the geometry feature. For example, reducing the laser power and increase the speed at the overhang region will help to reduce the melt pool, which yields similar melt pool size as the bulk materials. The module 2 here is focusing on the melt pool prediction based on the selected geometries and optimize the parameters to achieve similar melt pool depth for better surface finishing.

A mesoscale modeling approach tailored for the PBFAM process which can address the complexity and retain the benefits of a continuum scale methods has been implemented in this program. An open-source mesoscale simulation code LIGGGHTS which is built on an atomistic scale simulation engine LAMMPS was augmented to provide the required functionalities such as melt and-solidification dynamics.

Co-Cr alloy was selected due to the extensive experience at GEGR. Note that, specific materials properties have to be addressed in order to run the models. Co-Cr undergoes multiple thermal phase transitions including a competitive HCP versus the FCC phase formation dynamics depending on the cooling rate (Figure 8). Atomistic simulations were used to train the meso-particles sintering and the resultant properties were calculated to represent the cooling-rate dependent ratio of phases in the alloy matrix, providing the necessary inputs to the mesoscale model.

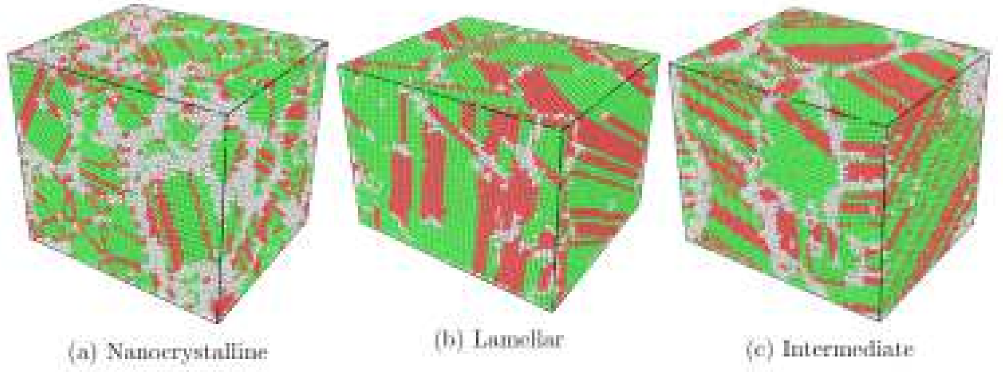

(a) Nanocrystalline (b) Lamellar (c) Intermediate

Figure 8. Atomic Scale model of cooling-rate depended microstructure

In the mesoscale model, the local melting process was represented using two distinct phase transitions: 1) transition to the hot melt-phase with smaller meso-particle with fluid like flow behavior, and 2) the gradual formation of the consolidated solid phase with cohesive energy density and mechanical property of alloys. This reactive mesoscale model utilized the energetic cost of melting and phase transition during solidification from atomistic simulation. The model is able to import featured geometries from the CAD model, pack with discrete elements or deposit layers of metal powder and simulate the trajectory of a laser beam with predefined spot size, speed, and power. The response of the metal powder as reflected in local melting, heat transport, and solidifications correlated to specific features that lead to part quality. An algorithm to launch multiple parallel simulations with different laser settings was developed based on MATLAB.

A case study of the integrated optimization is shown in Figure 8. A partially supported region was selected as this is a typical scenario in the revolving geometry where rod supports the overhang region. The geometry dimensions were shown in Figure 9(a). Note that, two different thermal conditions are expected: solid supported area with fast thermal dissipation and powder supported area with slow thermal dissipation. The model runs the laser back and forth with consistent P at 280W and V at 1000 mm/s. The predicted thermal profile is shown in Figure 9(b). The solid supported region shows much lower temperature as the powder supported area. The melt pool depth based on the temperature is shown in Figure 9(c). lower melt pool depth corresponds to the low temperature. In order to improve the scanning parameter, a different set of laser power and speed should be proposed at the powder supported region. The matlab tool run different set of laser power and speed to obtain the average melt pool depth for each case. Based on the required melt pool depth, a set of parameter, P = 270W and V = 800mm/s, was selected. Figure 9(d) shows the improved prediction on the melt pool depth. The difference between the melt pool depth as significantly reduced. However, due to the boundary effect, the parameter still can be improved through further iteration.

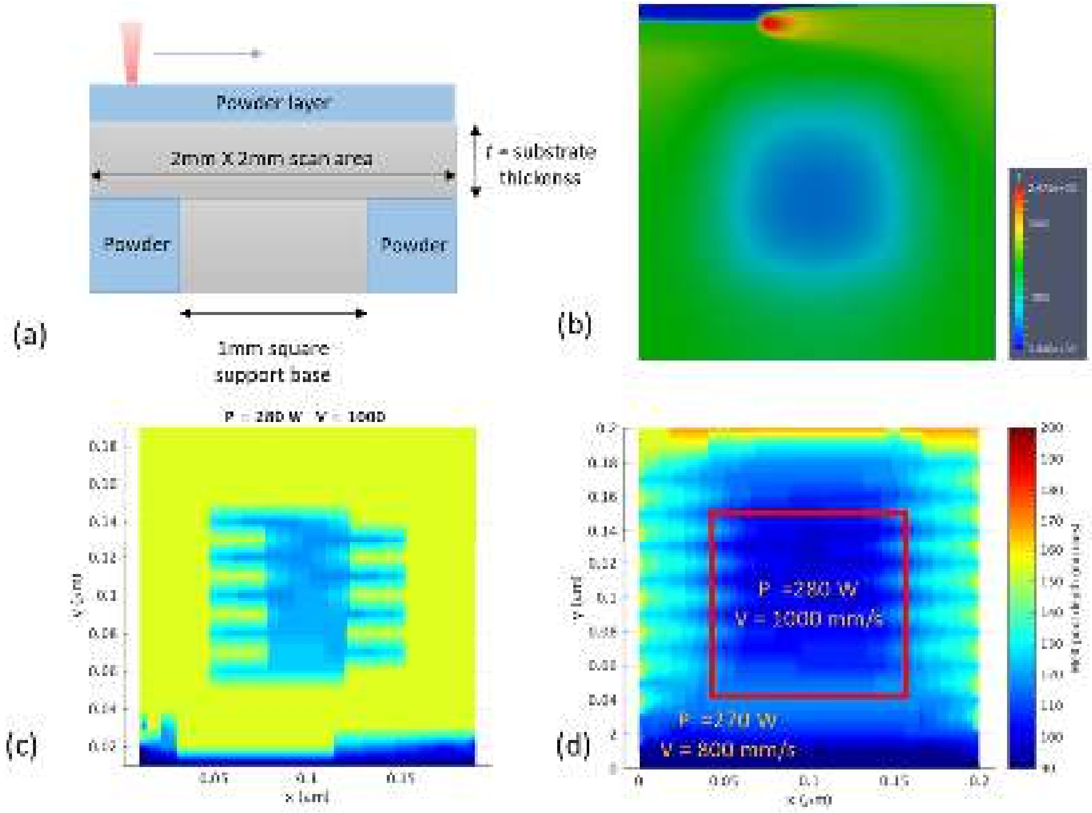


Figure 9. Mesoscale simulation on a supported layer: (a) model dimensions, (b) temperature profile, (c) predicted melt pool depth with uniform scanning parameters, and (d) optimized parameters

Module 3: Distortion Prediction and Geometry Compensation

GEGR led the effort to develop the FEA based process model to predict the distortion and stress revolution during the PBFAM process and heat treatment processes, and also develop a tensor morphing based geometry compensation algorithm to mitigate distortion with the machining stocks requirement. A simplified approach to model the PBFAM process has been developed at GEGR. A detailed scanning pattern with motion of microscale melt is supplanted by slice-by-slice activation. With each slice encompassing multiple build layers of actual process, the approach can yield superior computational efficiency while substantially capturing the transient physics of the process. The last status of predicted distortion, temperature, and residual stress from the PBFAM process model was the starting status for heat treatments. In the FE model, the activation process is based on the mesh applied to the geometry. To reduce the computational cost, each mesh layer contains 30 layers of actual powder layer. The model has predicted the same distortion tendency as physical as-built part. Due to the coarse mesh, the model overpredicted the distortion by 1.8 times for the revolving geometry and 1.5 times for the bracket. The detailed comparison was shown in Figure 10 for the revolving geometry and Figure 11 for the Bracket. The overprediction is largely due to the coarse mesh size used in the simulations in order to achieve the computational performance, which can lead to shorter iteration cycle time. This has been approved by applied much finer mesh with 2D assumptions. Since this is a general challenge for all simulation tools, not only the mesh size, but also the variations of materials properties can lead to either over- or under-predictions. In this project, we proposed to use experimental data as baseline to establish a scaling factor. So that the over- or under- prediction can be scaled to the correct magnitude. With fast iterations and the experimentally established scaling factor, the predicted results can replace the experimental results for geometry compensation.

GEGR has also developed an approach to compensate an input part geometry (nominal geometry in STL format) based on displacement field that was measured from a Coordinate Measuring Machine (CMM) or a x-ray CT system. A tensor morphing algorithm is used to map the discrete compensation field to a continuum CAD space by fitting an analytical function.

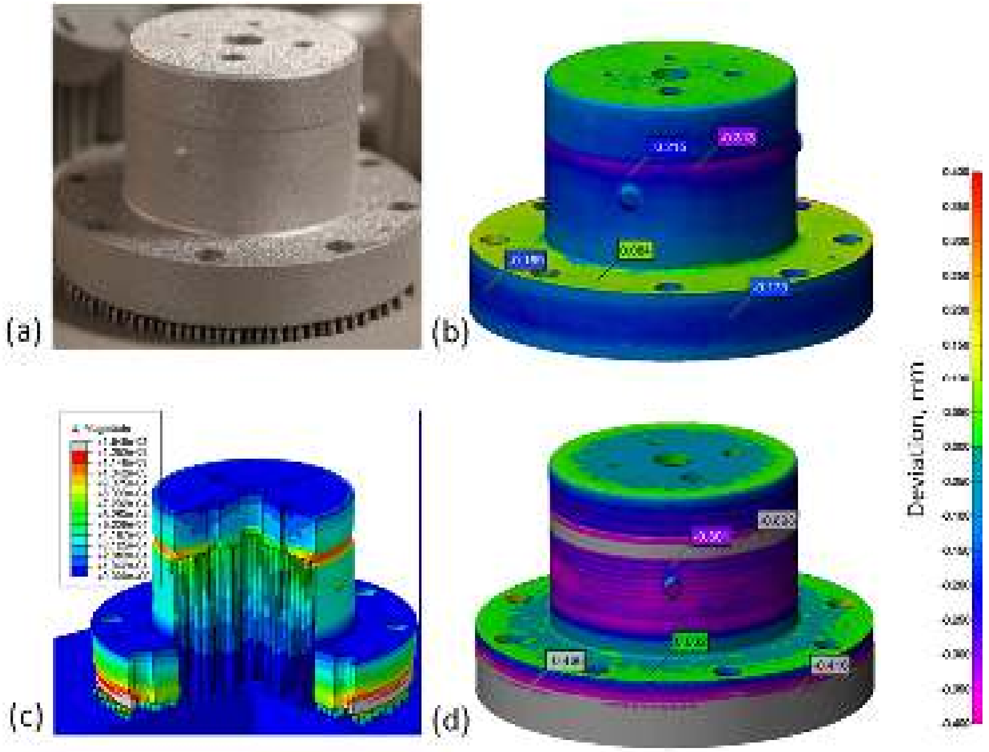


Figure 10. Distortion prediction for revolving part: (a) as-built part, (b) distortion deviation based on CMM data for as-build part, (c) predicted distortion, and (d) distortion deviation based on simulation

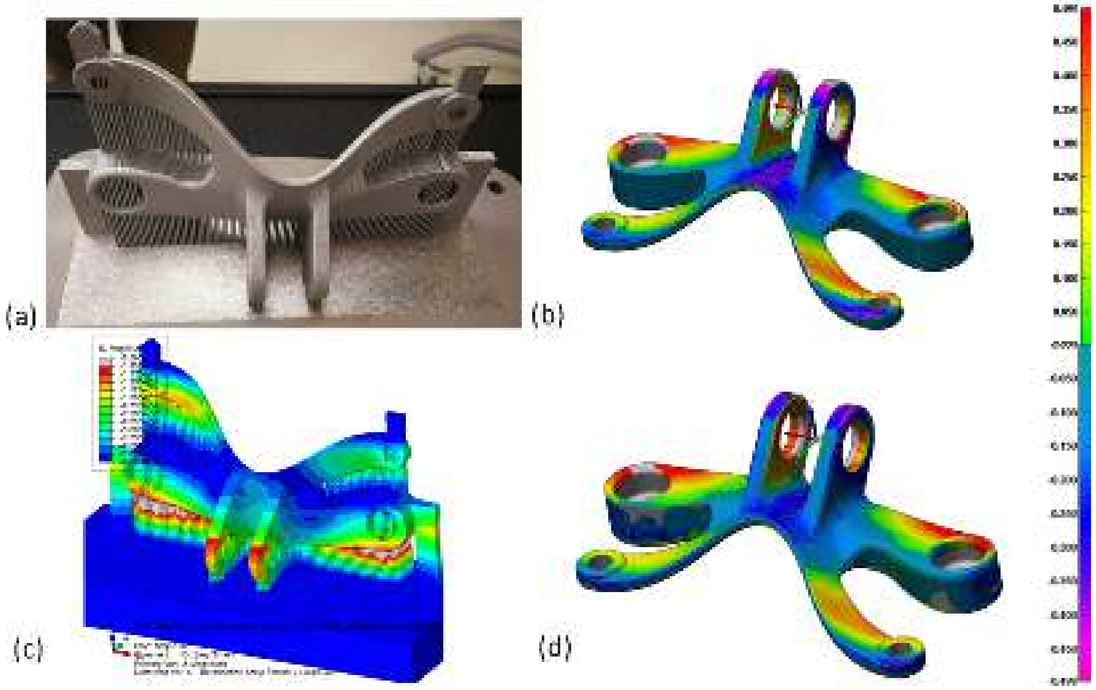


Figure 11. Distortion prediction for Bracket: (a) as-built part, (b) distortion deviation based on CMM data for as-build part, (c) predicted distortion, and (d) distortion deviation based on simulation

The distortion predicted by the FEA model was applied to derive the pre-compensation functions. With the consideration of post-machining, the machining stock was added to the displacement field. Compared to inspection data, less point density is expected from FEA mesh. Therefore, a high order of tensor that maps the nominal model were developed. Because of the highly non-linear behavior of the thermal distortion, the overcompensation factor was explored. This improvement was to reduce the number of iterations including FEA runs and physical builds. The morphed mesh was directly imported to the FEA model for a concessive iteration until the overall geometrical deviation is within a given tolerance band. A STL model was generated based on the intermedia compensation field and it was exported to the AM machine to build a physical part. CT scanning/CMM were carried out to collect the geometry information. Geometry data that is measured after each step were used for the validation of the geometry morphing algorithm and distortion prediction. 2 iterations have been performed for both the revolving geometry and the Bracket. Figure 12 shows the compensated distortion deviation map comparing to the nominal part without compensation. It can be seen that ~65% of the mean distortion deviation was reduced through the numerical iterations.

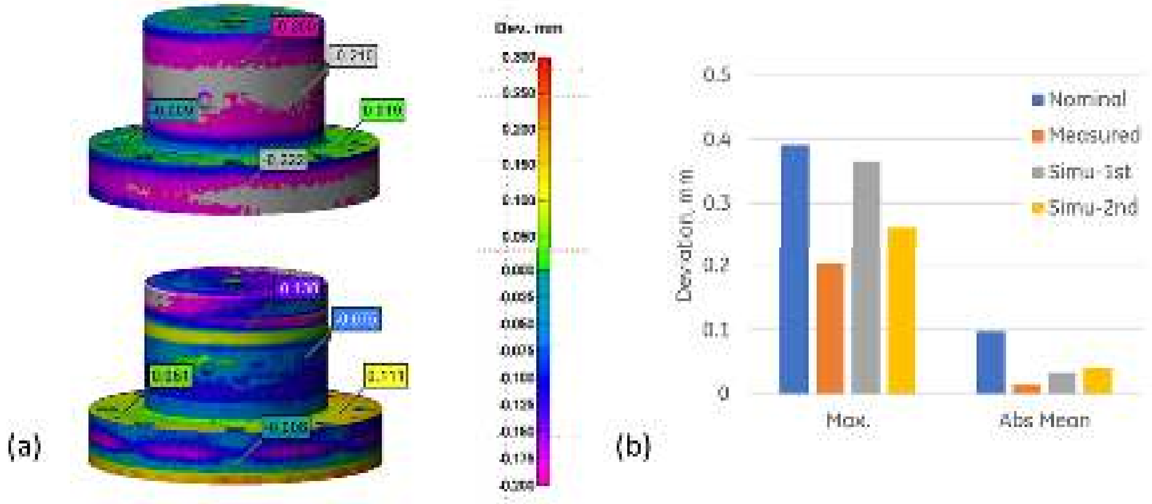


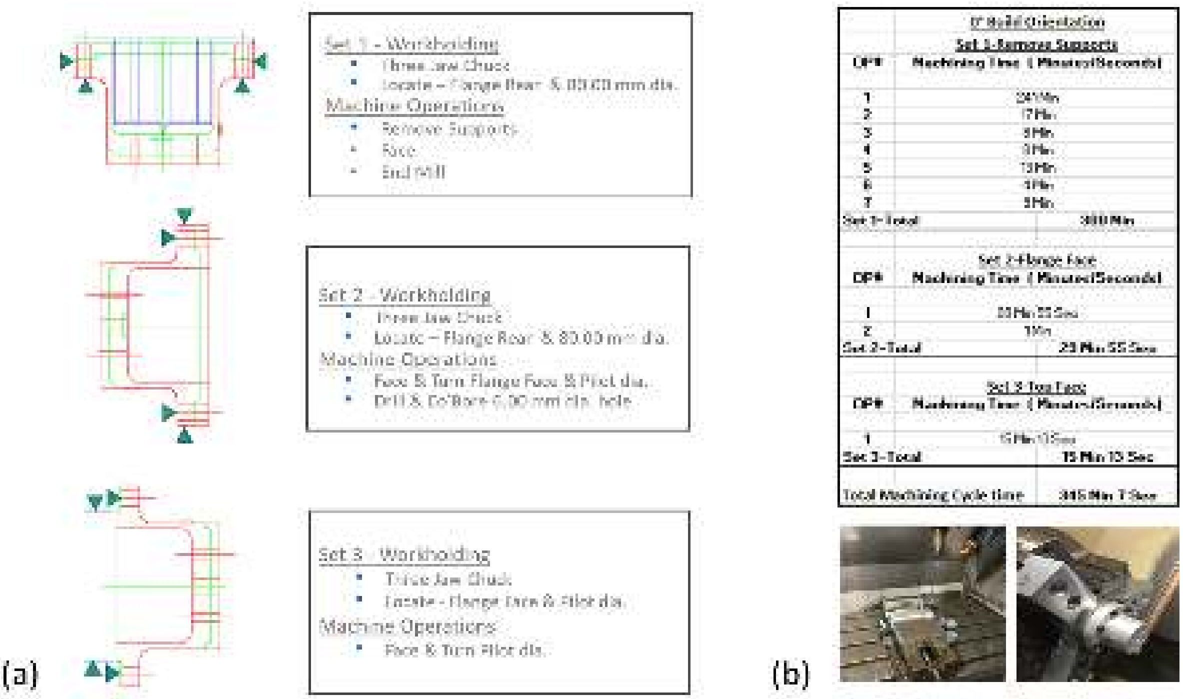
Figure 12. Distortion comparison: (a) deviation map for nominal parts without compensation vs. simulation based compensation after 2 iterations, and (b) maximum and mean deviation for compensated part based on measurement, 1st numerical iteration and 2nd numerical iteration.

Module 4: Machining Consideration and Verification

TechSolve evaluated the design with the consideration of predicted distortion to perform machining planning and also provided machining stock to enhance the modelling as it relates to post-process machining. Geometric attributes were first defined for each part feature and clarify any additional finished part requirements. These attributes were assessed against the known capabilities of the AM machine as well as the planned post-build treatments and machining necessary to satisfy all GD&T callouts. In addition, it provided associated stock requirements and the expected geometric tolerance and finish after fabrication. To develop the post machining procedure, the machining process for producing each of the machined features was reviewed by machining experts and analyzed in terms of accessibility and setups. the setup, work holding fixture options, machine requirements, tool list, cutting parameters, cycle times, and estimated machining cost for each machined feature of the part. Figure 13 shows the settings and the proposed operations for the revolving geometry and the documentation on the machining cycle time. Three setups were proposed, and the machine operations were defined based on the specifications from the part, such as, faces required machining, geometry tolerances. All these requirements were provided by the user and the machining experts provide feedback to the original CAD design in order to satisfy the AM process and take into account the distortion during the fabrication process.

Integrated work holding features are suggested for parts that do not fit into current work holdings. This is evaluated by the machining experts who has extensive knowledge on the current machining capabilities. The design is also provided by the machining experts to ensure that the work holding features can fit into the current machining systems. The automation of the work holding design and geometry generation is out of the proposed scope of this project. However, it is one of the topics which can provide further value in the pre-processing tool to establish an expert system to generate unique features based on the available capability. In this project, the work holdings were added to the part design manually and carried through the virtual verification process for enhancing the modelling iterations to improve or simplify the machining process. Figure 14 shows the extra features that were added to the Bracket. Machining equipment at TechSolve were programmed according to the associated model provided. Finished samples were inspected and measured to verify the expected finish and dimensional attributes of each feature.

The machining procedure can be adjusted, and feedback was provided to the modelling team. Figure 15 shows the completed revolving geometry with its comparison to the nominal geometry. It can be seen that after geometry compensation, the distortion was controlled within 0.05 mm.



Set 1 - Workholding
- Three Jaw Chuck
- Locate – Flange Rear & 80.00 mm dia.

Machine Operations
- Remove Supports
- Face
- End Mill

Set 2 - Workholding
- Three Jaw Chuck
- Locate – Flange Rear & 80.00 mm dia.

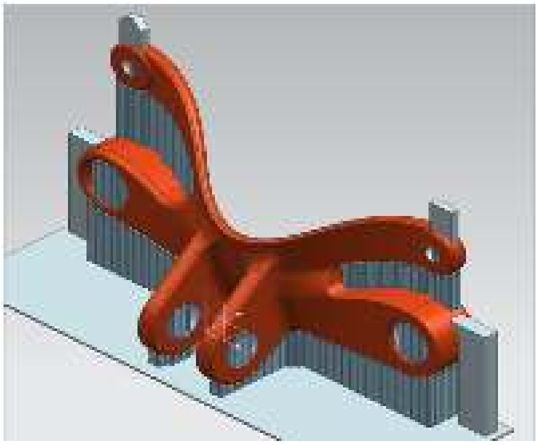
Machine Operations
- Face & Turn Flange Face & Pilot dia.
- Drill & Co'Bore 6.00 mm dia. hole

Set 3 - Workholding
- Three Jaw Chuck
- Locate - Flange Face & Pilot dia.

Machine Operations
- Face & Turn Pilot dia.

	0° Build Orientation
	Set 1-Remove Supports
OP#	Machining Time (Minutes/Seconds)
1	241 Min
2	17 Min
3	9 Min
4	3 Min
5	13 Min
6	4 Min
7	5 Min
Set 1-Total	300 Min
	Set 2-Flange Face
OP#	Machining Time (Minutes/Seconds)
1	28 Min 55 Sec
2	1 Min
Set 2-Total	29 Min 55 Sec
	Set 3-Top Face
OP#	Machining Time (Minutes/Seconds)
1	15 Min 10 Sec
Set 3-Total	15 Min 10 Sec
Total Machining Cycle time	345 Min 7 Sec

Figure 13. (a) machining procedure settings and (b) the record of machining cycle time



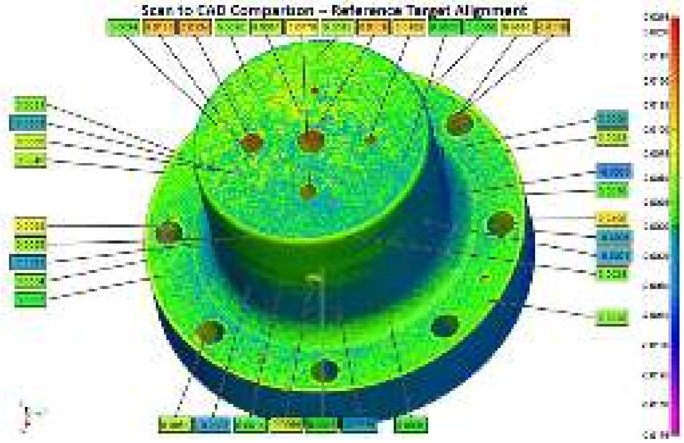


Figure 14. Added features for work holding

Figure 12. Machined part comparing to nominal CAD

III. KPI'S & METRICS

The proposed virtual toolset, including 4 major digital tools: 1) model-based producibility tool for PBFAM and machining; 2) PBFAM scan path optimization to ensure high material integrity; 3) prediction of thermally induced distortion; 4) part compensation for distortion and machining processes; was developed throughout this program. With the validation through a simple revolving geometry, after 2 numerical iterations, the distortion can be reduced more than 2 times with only 1 physical build which provides a baseline scaling parameter to anchor the high-efficient distortion modeling. The archived goals comparing to the proposal goas are listed in the table below.

Metric	Baseline	Goal	Results	Validation Method
Producibility evaluation	Manual operation (1-2 days) plus rework	Automated analysis in 0.5 day, more insightful with error-proofing capability	NX-based tool that automatically calculates Producibility index and generate support structures. More than 9 features can be analyzed. For revolving geometry, it only takes less than 10 mins to complete 1 cycle	The preprocess tool was validated through two geometries: 1) a revolving geometry and 2) a Bracket.
Physical process iteration per design	10 iterations (depending on part complexity it may need 100s of iterations)	4 or fewer iterations (moving more than 60% physical iteration to virtual space)	Three tools are completed to reduce the iterations: 1) Physics-based numerical model that predict the melt pool size, 2) distortion prediction, and 3) NX-based geometry compensation tool. These tools cover the major processes during the fabrication process and heat treatment process. Iterations in the virtual space provide a converged STL geometry for AM machine. Within 2 iterations, the mean distortion of the revolving geometry was reduced to 0.05 mm. For the revolving geometry, each melt pool simulation takes about 30 mins using 16 cpus. The distortion prediction takes ~ 2 hours using 8 cpus and the geometry compensation takes ~ 5 mins within NX.	The numerical tools were validated through the revolving geometry. With an applied scaling factor, after 2 iterations, the mean distortion was reduced to 0.05mm. the application of the tool to a complex bracket part shows similar results: the mean distortion was reduced to 0.03mm.

Total process development cycle time	10–18 weeks	2–3 weeks	With 1 baseline physical build and 2 numerical iterations, the completion cycle time can be dramatically reduced due to no waiting time for fabrication, heat treatment, machining and CMM data collection after each process. One physical iteration took almost 2 to 4 weeks, including fabrication, CMM, heat treatments, machining and one numerical iteration took about 2 days, including the modeling preparation time and running time.	Based on the physical process time including planning, fabrication, machining, heat treatment and CMM and numerical simulation time. For the revolving part, without simulation, 3 iterations are expected for the overall distortion control, which may take 8 to 16 weeks. This reduces to 3 weeks as 2 iterations were replaced by simulations.

IV. TECHNOLOGY OUTCOMES

The team has developed and validated an integrated framework and underlying digital toolsets to accelerate the PBFAM process certification, covering from CAD design, building process, post heat treatment to final machining finish. The virtual workflow is fully realized by knowledge-based and physics-based digital tools. With the assist of this virtual workflow, at least 2 physical iterations out of 3 are replaced by the models for a simpler geometry. For complex geometry, more physical iterations would be replaced by the numerical models. In general, the following benefits have been approved through a simple design part:

1. Develop an integrated framework and underlying toolsets to accelerate the Powder-bed Fusion Additive Manufacturing (PBFAM) process certification
2. Shift > 60% process iterations to the virtual world, leading to a 3X reduction in the certification time
3. Replace empirical process know-how with physics-based understanding
4. Reduce development time from 10-18 weeks to 2-3 weeks via automated workflow and extensive use of virtual digital tools

The developed four individually functioning tools has the following features:

1. A model based preprocessing tool. The tool will analyze the geometry producibility and highlight the possible problematic areas in the CAD design based on prior knowledge. Where support structure is needed, the tool will find the optimal orientation and add optimal support structure based on producibility rules.
2. Laser scanning protocol optimization model. The model will provide materials solidification characteristics based on alloy composition at high cooling rate and optimized laser scanning protocol for high materials integrity and low surface roughness.

3. FEA based distortion prediction model. The model will predict the distortion and stress evolution during the PBFAM process and heat treatment processes. Cracking criteria will determine the cracking tendency based on predicted stress evolution.
4. Geometry compensation tool. The tool will morph the geometry using highly non-linear functions to compensate both distortions predicted in FEA model and machining stocks.

Digital tools, user manuals, demonstration cases and recorded videos on how to use the tools are provided as deliverables separately. Please contact DMDII for the access.

The designed use cases are to reduce the time and cost to accelerate the process certification for the LPBFAM process. Two scenarios are provided below:

a. DMDII membership use case: As a design/manufacturing engineer, I can utilize the framework and case study developed by this project to choose AM-friendly printing orientations and laser parameters to control residual stress and distortion. The part will come out with correct tolerance with minimal number of physical rework and iterations. This will enable me to accelerate the process development time and reduce cost for introducing new parts.
b. Commercialized solution use case: As a design/ manufacturing engineer, I can extend the capabilities of my current digital tools by installing the add-ons to my CAD solutions and running FE simulations without purchasing extra specialized software packages. This will give me confidence on pre-processing and also flexibility to evaluate process conditions for both existing problematic parts or developing new parts.

III. ACCESSING THE TECHNOLOGY

All the tools that are developed through this project are free-of-charge for DMDII members. They are available to download from DMDII website. Any specific requests can be made to DMDII or the PI.
Beside the extensive knowledge in AM, the following knowledge and/or skills are also required to run the tools. For pre-processing tool and the geometry compensation tool, the basic understanding and operations of Siemens NX are sufficient to run the two tools. For the melt pool prediction tool, basic knowledge on program is required in order to access the scripts and do modifications based on the understanding of physics. Since Matlab is used to communicate between model setup and numerical solver, sufficient skills on Matlab is preferred. Opensource code, OpenFoam, provides the solver. How to submit running cases through OpenFoam is also required to run the generated input files. For the distortion perdition tool, to better understand and take full control of the tool, the experiences of running FE model is critical. Although running the tool does not require FE knowledge, understanding the results and improve the numerical convergence issue for complex geometries do need solid FE knowledge. For simple geometries, the Python script can automatically complete the mesh for FE simulation. However, for complex geometers, due to the layer-wise meshing strategy, adjustment has to be done based on the actual geometry , although certain algorithms have been implemented in the Python code.

The following IP will be claimed by UC.
1. Each design for additive manufacturing module developed in the program, including: Small Openings detection, Thin Feature detection, Sharp Corners detection, Thin to Thick Transition (and Thick to Thin Transition) detection.
2. Support generation and support parameters (support contact area, support volume, down facing surfaces)
3. Support Accessibility

4. Producibility Index and Orientation Optimization.

Specific software or platform is required to run the tools. The details are listed below.

Tool	Software/Platform	Note
Pre-processing Tool	Siemens NX	Developed based on version 10.0
Melt pool simulation tool	Physics-based modeling: OpenForm Visualization: Paraview Automated script: MATLAB	OpenForm runs on Linux system, supporting High Performance Computing
Distortion prediction tool	Finite Element tool: Abaqus Automated script: Python Mesh: Altair Hypermesh	Both Abaqus and Hypermesh can be replaced by other FE solver or mesh tools. However, the current tool specifically outputs Abaqus input file. Extension to other FE solver will required modification of the source code to generate the solver-specific format. Simple geometries can be meshed automatically based on the provided scripts. Complex geometries may need certain manual work to fit local errors
Geometry compensation tool	Siemens NX	Developed based on version 10.0

VI. INDUSTRY IMPACT & POTENTIAL

The Additive Manufacturing (AM) market reached $7.3 billion in 2017 with a compound annual growth rate of 21%. The massive potential of AM relies on its ability to produce complex, hitherto un-manufacturable geometries, lower buy-to-fly ration, minimum scrap waste, and less lead time, which enables on-demand bespoke manufacturing and radically disruptive supply chains. The current research and application has largely focused on directly producing complex shaped functional metallic parts Direct parts fabrication via PBFAM grew more than 50%, and stronger growth is expected to continue with significant announcements of AM products from large OEMs

The toolset can be utilized by manufactures at different stages. For products that are under development, the independency of each tool provides the benefit of allowing manufacturers to choose one or two of the tools to specifically examine their current issues and also choose a tool to guide the next step. This would not disrupt the original plan but effectively assist execution for the current process development. Note that the tools do not limit to AM processes. The distortion prediction for heat treatments and morphing algorithms for the heat treatment distortion and machining stocks can be generally used for conventional manufacturing processes, which will benefit manufacturers in general. For new products, the toolset will fully unleash its benefits to provide solutions for the entire process certification, from original model design, to intermedia process model design, to machine parameter setting, and to final machining verification. Taking GE's LEAP fuel nozzle for example, with limited assistance of digital tools, hundreds of experimental iterations were done to overcome morph distortion and surface finish issues, which spanned for several years. With the application of the multidisciplinary toolset, we anticipate at least 60% fewer physical iterations to sort out distortion problems. This translates into several million dollars during the development cycle towards process certification.

This work allows the burgeoning AM industry to broadly adopt these modeling and simulation technologies, thus accelerating and standardizing their process certification methods. The project will also unlock tremendous value for small and medium size AM service providers and original equipment manufacturers to turn art-to-part in weeks instead of months with significant cost savings

VII. TECH TRANSITION PLAN & COMMERCIALIZATION

Workshop has been conducted at DMDII to both promote and demonstrate the capability of the tools. Each tool together with the integrated toolset has its own user manual with detailed illustrations. This provides opportunities for new users and tool enthusiasts to explore the tool without training. With sufficient documentation and training videos, it expects to help to hire, train, and sustain the requisite number of personnel using advanced numerical modeling and simulation techniques on AM processes. This is also critical for the future of manufacturing as the digitalizing revolution is occurring now.

The developed tools through this project are open to all DMDII members free-of-charge. Currently, the team is engaging with a couple of members to continue to evaluate the tools and support members' applications. These evaluations will provide further validations for the developed tools and also raise the questions on how to further improve the current toolset. However, due to lack of funding support, the effort is very limited, and a long-term support plan should be considered.

The preprocessing tool developed by UC team has gained strong interest from Siemens NX to consider a path for commercialization. Actively conversations have been in place. Since there is certain background IP associated with this tool, UC team will continue the conversation and figure out the best way with DMDII to move forward. Both the distortion prediction and compensation tools are now available in other commercial tools. Note that the development of commercial tools to predict distortion and stress has grown exponentially in recent years, for example, Autodesk, Ansys, Geonx and Simulia. However, since the team took a more general solution where no specialized tools are required other than general FEM solver and mesh tools, most of the companies can adapt the tool for their current applications. Through the scripts, modeling experts can customize the functionalities to carry out advanced studies on residual stress and distortion prediction, such as examining the optimal sequence for scanning patches. As the development cycle of the commercial software, new functions may not be released or the users have to wait for a long period to access the new capability. The current tool provides the model developer a flexible platform to examine new ideas. On the other hand, the reliability and user interfaces are compromised. Sufficient documentations or tutorials were provided through this project. however, further support requested by DMDII members may be limited due to funding support.

The nature of this tool links the processes of AM. The current effort is mostly focused on distortion control and melt pool size control. There are other important perspectives in the AM can be leveraged and further developed through this framework. The future plan can focus on 1) improvement of the NX-based tools, including both pre-processing tool and the geometry compensation tool. Since most of the manufacturing companies own certain type of CAD software, it is much easier to adopt the current technology to their current practice. The collaboration with CAD companies will be essential for the success. 2) advanced capabilities beyond stress and distortion. This includes but not limited to microstructure prediction, cracking and porosity perdition, and lifing prediction to extensively extend the current capability. Since the commercial tools still mostly focus on stress and distortion, but moving to this direction. The research on defects and microstructures is still going on due to the complex physics. Leveraging this platform, different algorithms and criteria can be tested earlier to make an impact to the industry. Also, high cost is associated with all the commercial tools. This platform provides an low-entry level for manufactures to take the advantages of digital manufacturing.

VIII. WORKFORCE DEVELOPMENT

The development and demonstration of virtual certification capability for the scenario of AM provide material that can help to condition the environment for the wider introduction of this technology and approach. The insights and experiences developed during the execution of the technical approach can create new material with a message focused on the opportunity that effective enhanced modelling presents a paradigm shift in our approach to process certification.

The academic component redefined the manufacturing engineering curriculum at the 4th year college and graduate level and introduce new elements into the traditional engineering curriculum to enable current and future generations of manufacturing engineers to fully leverage the benefits of virtual process/product certification enabled by enhanced modelling. At UIUC, a short course on virtual manufacturing as part of Integrated Computational Materials Engineering was offered through Computational Science and Engineering program by Prof. Chaudhuri. At UC, the results of the AM part design to manufacture the validation toolset developed in this project was adopted into two graduate courses titled “CAD for Manufacturing” (senior and graduate level) and “Precision Engineering and Computational Metrology” (graduate level), and a new “Geometric Modelling in Additive Manufacturing” course, all taught by Prof. Anand.

Current practitioners in the relevant industries were encouraged to consider enhanced modelling capability as a “game-changer” technology that will compress the time required to adopt and implement new product/process technologies. The focus has been on creating awareness of emerging enhanced modelling technology capabilities and applications as well as how they relate to overcoming hurdle factors in moving from the current certification environment to a model-based environment and developing practical tools for assessing and evaluating modelling technology for best application as well as practical steps to implementation. The industry team members for this project each have a certification process and participate in the aerospace, defense, and commercial sectors. This also provides the opportunity to explore the experiences and approaches relative to incorporating a virtual certification approach into an existing process/product certification environment that has a certain amount of rigor associated with it.

IX. CONCLUSIONS

GE Global Research worked with the University of Cincinnati, the University of Illinois at Urbana-Champaign, and TechSolve and developed an integrated framework and underlying toolsets to accelerate the process certification for LPBFAM process. Model-based and physics-based digital tools were developed to cover the process from art to part, including 4 major modules: 1) model-based producibility tool for PBFAM and machining; 2) PBFAM scan path optimization to ensure high material integrity; 3) prediction of thermally induced distortion; 4) part compensation for distortion and machining processes; 5) machining consideration and evaluation.

Through the integrated framework, the virtual process realizes real-time pre-processing to check geometry features and automatically add support structure, and also early consideration of post-processing. It treats the part design, PBFAM process, heat treatment processes, and machining as an integrated value stream, therefore, avoiding significant rework due to the sequential natural of the physical process. Meanwhile, the feedback from the pre-processing tool, distortion prediction, and machining verification provides a clear objective to guide part redesign. By utilizing the developed virtual toolset and demonstrated through a designed revolving geometry, more than 60% of the physical iteration was able to be moved to the virtual process. This leads to a 60 to 70% savings in both energy and raw materials arising from the reduction in process iterations. With the automatic flow and the assistance of high performance computing, a more than 3 times reduction on the cycle time is achieved due to much less physical iterations, inspections, and verification. Through the demonstration of a designed revolving geometry, the mean distortion was reduced more than 70% through 2 numerical iterations. This is also applied to a public Bracket part. Each individual tool also serves its unequal capabilities for producibility, support structure design, distortion and residual stress prediction, compensation for distortion and machining, and post-processing tolerances. The independency of each tool also provides tremendous flexibility to customers to focus on one or two problematic areas of most concern.

The developed toolset allows the burgeoning AM industry to broadly adopt modeling and simulation technologies, thus accelerating and standardizing their process certification methods. The team envisions that this will unlock tremendous value for small and medium size enterprises (SME) and also Original Equipment Manufacturers (OEM) to turn design to product in weeks instead of months with significant cost savings.

The extension of this program looks into further evaluating the toolset with manufacturers, supporting DMDII members to adopt the numerical-oriented technology, commercializing the developed tool and extending the capabilities to cover a broader perspective of the AM process under this developed framework.

X. LESSONS LEARNED & RECOMMENDATIONS

Throughout the development of the current toolset and collaborations among different institute, the lesson-learned and suggestions are made below based on each working group:

1. Development of the preprocess tool

The pre-processing tool can detect a range of different manufacturability problems that arise while building a part. It provides a good starting point for industries exploring additive manufacturing as an option for fabricating complex, functional parts. The Producibility Index (PI) tools help the user to identify the most optimum build orientation by quantifying the goodness of a part. However, these tools need considerable time to process the large number of orientations. In theory, all orientations should be evaluated without constraints. This will lead to numerous cases as the combinations in all x, y and z directions. To effectively optimize the process, advanced data structures and algorithms can be explored to reduce these computation times. Through limited number of orientation evaluations together with constraints that are provided by the user, the selection process of orientation can be effective.

The preprocessing tool generates two types of supports: solid-based and surface-based supports. Both rod-type (solid) and honeycomb-type (surface) were evaluated through the two geometries. Both support structures perform well for a variety of part surfaces in the parts built. However, the selection largely relies on the stress level at the supported location. Honeycomb supports as well as support teeth provide easy removal during post-processing machining.

2. The current version of software tools works only within the Siemens NX modelling environment. Programming using open source CAD and geometry libraries can be implemented to make the tools compatible with another CAD software. The challenge becomes the selection of reliable open source CAD and geometry libraries and the acceptance of the CAD system. As legacy reasons, manufacturing companies have their preferred CAD tool. The program languages for all CAD tools take different syntax and functions. This still requires different development for different CAD tools although it realizes the same functions. Mesoscale melt pool model

Properties that predicted by atomistic scale model show a good qualitative prediction on the absolute values. This is due complex materials systems with unknown model inputs. The application of the atomistic model is still not mature enough to replace necessary experimental measurements.

Mesoscale melt pool simulations bridge process parameters to solidification and defect characteristics. Arbitrary scan path and power inputs can be imported byrunning scripts through simple text file interface generated through this program. However, calibration for input parameters is still required due to limited materials database for high temperature properties, surface tension and laser absorption coefficient. Limited domain size and geometry features can be evaluated due to the computational efficiency. It has been found the upper bound on feasible analysis area: ~1cm^2, 1mm thick, which defines the characteristic length for the simulation. Applications to the entire geometry is still challenging even with supercomputers. Further simplification and/or advanced algorithms with data analytics are required to accelerate the calculation. On the other hand, depending on the accuracy, the calculation based on the limited domain still provides sufficient insights of the process. The optimization based on the limited domain will significantly improve the current scan path generation. Leveraging historical data with current development machine learning will further help the optimal settings of scanning paths.

3. Macroscale Finite element model

The Abaqus based tool accurately captured the part distortion, stress, and cracking tendency as long as the model was highly refined (for example, the size of the mesh layer is similar to the actual powder thickness). For less refined models where the size of the mesh layer consists of tens of actual powder thicknesses tended to overpredict the displacement and had to compensate using a scale factor. The stress and cracking prediction also had a significantly increased uncertainty with less refined models.

While we did automate slicing and mesh generation, in practice, this can fail with complex geometry due to either the slicing operation producing bad geometry or poor-quality mesh. Tet meshing additive parts usually involves manual repair to get a good quality mesh.

The final tool version includes solver parameters that are much more forgiving regarding convergence; however, if convergence difficulty is encountered, the user may have to locally improve the mesh quality and restart the analysis. One improvement that should be made is to add a couple of fast calculation options for DOEs or large models (one option to apply temperature instead of flux or perhaps add inherent strain option). Another option would be to add a voxel-based option to mitigate the meshing difficulty.

4. Geometry compensation tool

The current version of tool only works within the Siemens NX modeling environment. This is similar to the preprocessing tool. Improvement is required to be compatible to other major CAD software.

The tool works for both experimentally measured data from CMM and numerically predicted data from finite element models.

The "scaling factor" option in the tool mitigates over- or under- compensation. It also helps to calibrate simulated deviation with physical measurement. This calibration helps the compensation process converge faster High quality (accuracy) deviation data calculation is critical to a success Inspection-based Compensation. Normal and curvature filter helps to filter low quality data out before compensation, which improves accuracy of a compensated model. However, A quality index of deviation data should be developed to measure the quality of deviation data.

The current compensation Tool still rely on the STL file. Since STL is still the dominant format that is imported to the machine for printing, this does not affect the applications of the current tool. However, STL is still based on the triangulated surface. Interaction with native CAD (a NURBS/B-spline B-Rep model) in solid format will provide all the available functions in the CAD software to carry on further operation. . A preliminary result shows that maintaining a watertight topology is a major challenge of morphing a NURBS/B-spline B-Rep model. This work should be carried out with CAD software developers to fundamentally interact with the solid model with error-proof operations.

5. Machining tolerance and post machining procedure develop and verify

Different types of support structures were machined through this project. it has been found that thick supports machine the same as solid material, however they pose a safety hazard when supporting external features. Rod supports break away easily but are not feasible in a machining environment. Especially on internal features, honeycomb supports are necessary due to the rigidity necessary to cut material in this family (hardness).

3D printing parts with long or thin features, due to distortion, do not pair well with machining. Parts to be printed need a selected feature in an area of least distortion to be dimensioned for use as a machining reference.

Due to support structure, specialty fixtures are required to reduce set-ups. This is because that the standard work holdings and tools may not fit the current part design. Custom tooling needs to be evaluated. Turning cutters are not always necessary for certain support structures. Guillotine type tools can be utilized in some cases. Completed as-built models are necessary at the same time as the part. Machining experts should review the part design with the support structure before the printing process to suggest additional features and avoid rework This allows a fixture to be preplanned instead of on the fly for each cut. Complete production plans and a formal process similar to "change request" are useful to keep track of R&D type parts and projects.

XI. APPENDICES

Through this program, items that are classified into 5 cataloged are listed below.

1. **Digital tools and their user manual/tutorials**: these include 1) A model based preprocessing tool. The tool will analyze the geometry producibility and highlight the possible problematic areas in the CAD design based on prior knowledge. Where support structure is needed, the tool will find the optimal orientation and add optimal support structure based on producibility rules. 2) Laser scanning protocol optimization model. The model will provide materials solidification characteristics based on alloy composition at high cooling rate and optimized laser scanning protocol for high materials integrity and low surface roughness. 3) FEA based

distortion prediction model. The model will predict the distortion and stress evolution during the PBFAM process and heat treatment processes. 4.) Geometry compensation tool. The tool will morph the geometry using highly non-linear functions to compensate both distortions predicted in FEA model and machining stocks.

2. **Geometry data for model validation throughout the process**: these include the original CAD model for the designed revolving geometry and the Bracket. The scanned STL files and the compensated STL files are also included for each process step for potential usage validation purposes.
3. Educational video: these include two videos that captures the basis and application of the toolset and basic knowledge of the entire manufacturing processes. One is at full length to cover all the details of the tool and the other is a short version as summary of the key capabilities of the toolset.
4. Close-out documents: these includes the final report, IP claims and other requested documents.

All the technical details and the demonstrations can be found through the final presented materials. Please refer to the deliverable for the access of the digital tools and user manuals.

The technical reports are detailed in the final presentation “DMDII_15-07-05_Closeout_Final.pptx”:

Tasks	Report Location
Task 1 Model based pre-processing tool (UC)	Slide 12 - 30
Task 2 Mesoscale laser-powder interaction model	Slide 31 - 55
Task 3 : Distortion and residual stress prediction	Slide 56 - 72
Task 4 : Tensor morphing based geometry compensation tool	Slide 73 - 90
Task 5 : Machining tolerance and post machining procedure development and verification	Slide 91 - 103