

# Additive Manufacturing Simulation Tools in Education

Sam Anand\*, Omkar Ghalsasi, Botao Zhang, Archak Goel, Srikanth Reddy, Shriyanka Joshi  
Siemens PLM Technology Simulation Center  
Department of Materials and Mechanical Engineering  
University of Cincinnati, Cincinnati, OH 45069, USA.  
anands@ucmail.uc.edu

Gil Morris  
Academic Partner Program  
Siemens PLM Software, Inc.  
Detroit, United States  
gill.morris@siemens.com

**Abstract**—Additive Manufacturing is becoming a strategic initiative to enable the transformation of today’s business into a digital enterprise. This technology is increasing the rate of innovation with new lightweight and sustainable designs and dramatically reducing the time from product ideation (design) to realization (manufacturing). Makerspaces are being built all over the world, especially in academic settings and students have 3D printers readily available to design and produce innovative ideas on the spot. The University of Cincinnati (UC) is partnering with Siemens PLM Software to create students who are ready for the digital workforce of the future considering the entire product lifecycle. UC is developing curriculum to teach the fundamentals of Additive Manufacturing using Siemens PLM software as a foundation using a cradle to cradle approach. Students will realize the idea of a ‘digital thread’ that connects a product design to its production environment using fast product/process simulations using a cradle to cradle approach. They will also become aware of simulation tools required for assessing and iterating the performance attributes of the process and the product between the ideation and realization phases to create a ‘digital twin’ of that product. This will help prepare students for Industry 4.0.

**Keywords**—Additive Manufacturing; Digital Thread; Digital Twin; Simulation Tools; Sustainable Design and Manufacturing

## I. INTRODUCTION

Additive Manufacturing (AM) is a group of processes that deposits material in layers to form a 3D part and is fast replacing traditional subtractive manufacturing processes to form fully dense parts. This paper details the development of

computational geometry-based preprocessing and simulation tools for assessing and iterating product designs and attributes of the additive manufacturing process in order to create a ‘digital twin.’ University of Cincinnati faculty have partnered with Siemens PLM to integrate these tools seamlessly within the Siemens PLM NX environment using C++, NX API and Ufunc routines. The paper focusses on a set of model-based and Design for Additive Manufacturing (DFAM) tools for Powder Bed Fusion Additive Manufacturing (PBFAM) processes for realizing the idea of a ‘digital thread’ that connects a product design to its production environment within the Siemens PLM NX environment. The workflow, as shown in Fig.1, starts with a part design and automatic support generation module that generates CAD-based support structures along with a GUI for customizing support types and the selection of support structure parameters. In the next step, several sequential stand-alone modules with associated GUIs have been developed for detecting various problematic DFAM features and support structure parameters on the fly that enables the user to detect manufacturability problems during the AM part build. DFAM features such as thin regions, thin walls [1][2], sharp corners [3], small openings [4], thin-to-thick and thick-to-thin transitions [5], and recoater arm collisions [6] are analyzed in a layer wise manner and are highlighted and displayed to the user within the NX environment. In addition to this, GUI based modules have been developed for estimating material consumption, part build time and surface finish based on support structure volume,

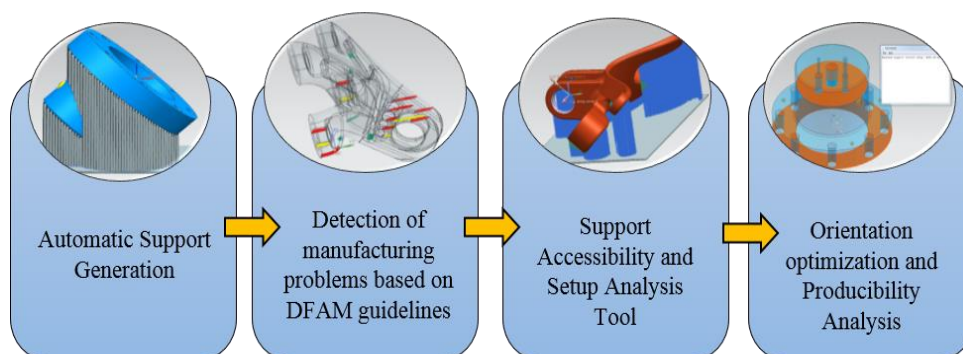


Figure 1 Workflow for the virtual pre-processing additive manufacturing tools

support contact area[2], hatch areas and down facing surfaces [4] that do not need supports. The tool also includes a support accessibility and setup analysis tool [7] that determines the extent of the support structures that can be removed using an EDM type machine tool during the post-processing phase of the AM work flow. Finally, all the DFAM and support structure parameters are brought together in a weighted multi objective optimization model based a unique metric termed as ‘Producibility Index’ that provides an indication of part buildability in a given build orientation [8]. The Producibility Index metric is then used for automatic build orientation optimization that will result in problem-free part builds and post processing.

These NX based tools have been integrated into a learning environment for a senior/graduate level course titled “Geometric Modelling in Additive Manufacturing,” that will be offered starting Spring 2019. In addition, these simulation-based tools have been integrated into a junior level “Manufacturing Processes,” and a senior/grad level “Introduction to Additive Manufacturing” course. The next few sections provide details and examples of the Additive Manufacturing tools developed within the Siemen NX environment.

## II. VIRTUAL MODELLING OF CURVES AND SURFACES- A PRECURSOR

### A. Design & Analysis of Hermite Curves

Hermite curve is one of the basic curves in geometric modelling that is defined by end points and tangents. A GUI for simulating this curve has been developed within NX. This tool is used within the course for demonstrating the impact of change in curve parameters on the shape of a Hermite curve. Students are assigned problems to create Hermite curves with various parameters and subsequently use this tool for visualizing and validating their work. Fig. 2 gives an example of Hermite curves created using the customized GUI.

### B. Design & Analysis of Bicubic Hermite Surfaces

The Bicubic Hermite Surface, as shown in Fig. 3, is a 3-D extension of a Hermite Curve. The Hermite surface is defined by 16 parameters (4 end points, 8 tangent vectors at end points, and 4 twist vectors). It is challenging for students to understand the understand changes in the shape of the surface as the parameters are varied. A GUI allows the students to vary the surface parameters and simulate the behavior and shape of this surface. The students use this tool in conjunction with their course assignment in visualizing and validating their work.

## III. DIGITAL TWIN FOR POWDER BED FUSION AM PROCESSES

### A. Support Structure Generation

Support structures are needed to support overhanging features during Additive Manufacturing part build. It is important to consider the support type and its volume prior to the build as these considerations affect the time and material needed for the build. In this NX application, students are asked to examine a part design at different build orientations and identify the locations needing support structures and follow this

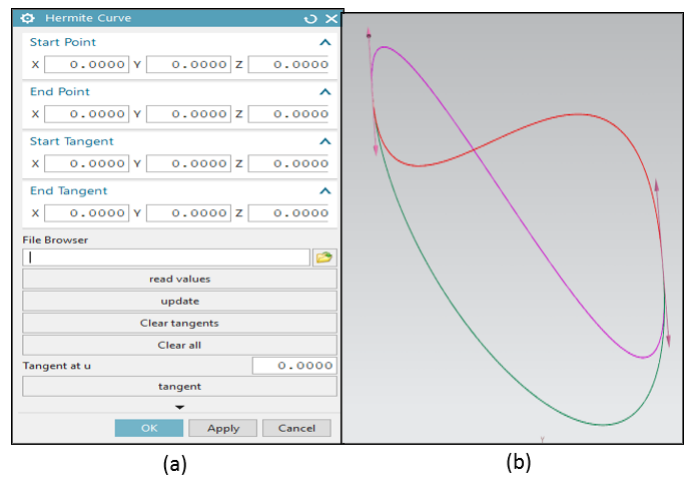


Figure 2 (a) GUI created within NX and (b) Plot of different Hermite Curves using the GUI

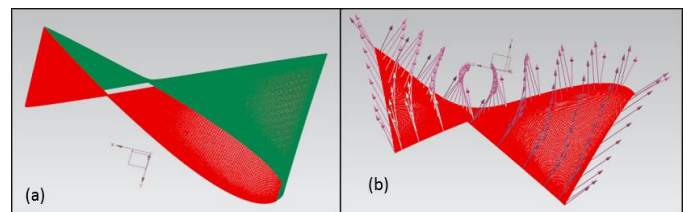


Figure 3 (a) Hermite surface with different parameters (b) plot of Hermite surface with normals across the surface

up with calculating the support volume and support contact area [2]. The objective of this course assignment is to introduce students to various AM file formats, and conduct calculations and analysis to simulate support structure generation for an AM build part. Fig. 4 shows NX visualization of support structures for a sample part. Fig.5 shows the numerical output regarding build time, support parameters and the GUI used within NX.

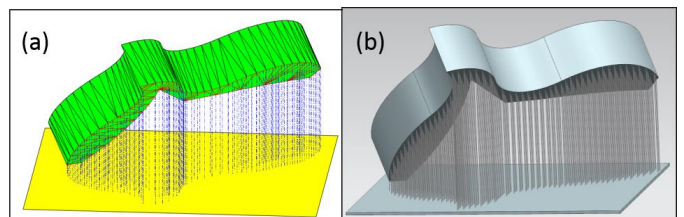


Figure 4 (a) Support Structure visualization in MATLAB (b) Visualization using NX tools

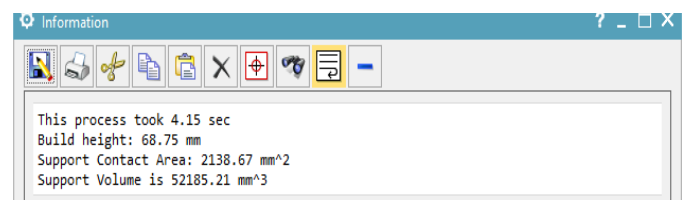


Figure 5 Output obtained using NX modules for support structure generation and calculations

Before fabricating the part using AM, it is vital to make decisions about the build orientation because since it directly affects all downstream operations involved in the process. The students were thus able to understand the importance of choosing the right type of support structures, build orientation as well as layer thickness and the effect of these decisions on downstream activities such as support removal and post-processing. This tool helps them identify potential areas for cost and material savings during the AM part build.

**B. Detection of Manufacturability Features**

Before proceeding to building a part using AM, the geometry needs to be analyzed for certain features that might pose a problem during the build due to the inherent process constraints. Separate stand-alone modules with GUI's were developed within the NX environment that allowed the students to conduct the analysis on sample geometry. Fig. 6 show the GUIs for two of these modules - small openings and thin to thick transitions [5]. In all the DFAM modules the part is first divided into several layers depending on the user-specified layer thickness for a given. The problematic features are highlighted in each pertinent layer as shown in Fig. 7.

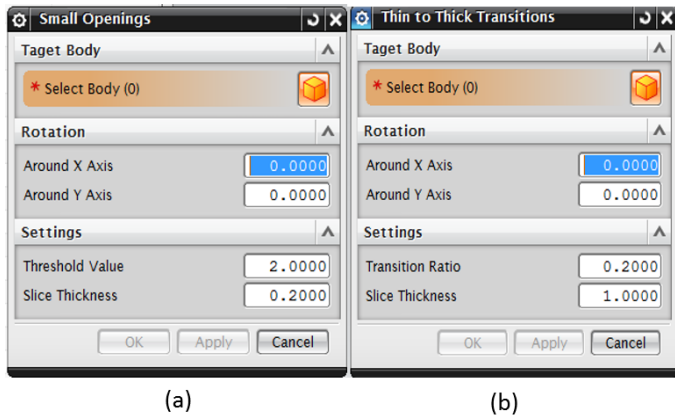


Figure 6 GUI design for detecting (a) small openings and (b) thin to thick transitions

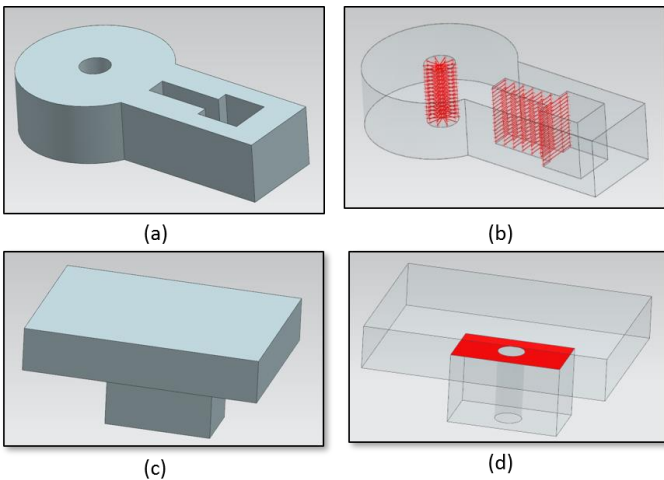


Figure 7 (a), (c) Testing parts and (b), (d) highlighted small opening features and thin to thick transition feature

Students were able to simulate the layer-by-layer process analysis using a virtual toolset that allows detection of several important DFAM features including sharp corners, thin regions/walls, small holes and transition areas for a given part build orientation. This analysis helps the students identify problems in the existing design from a manufacturability viewpoint and make appropriate design changes before building the part in a specific orientation. This enables the user to identify manufacturability problems and correct them at the design stage thus preventing multiple iterations of manufacture.

**C. Re-coater Arm Collision**

The re-coater arm, which is responsible for depositing each layer of powder, may collide with the part geometry if the part has a long edge parallel to the re-coater arm [6]. This can lead to damaged parts and material wastage. To simulate this behavior, a computational tool has been developed that detects and highlights the locations of part-recoater arm collisions as shown in Fig. 8.

Students will be able to utilize this knowledge and come up with a better part layout plan, build orientation and part design that prevents these collisions from happening, thus preventing rebuilds and material wastage.

**D. Detection of Thin Walls**

This module helps in identifying thin walls in the part and highlight them to the user. It is necessary to detect thin walls as they may cause build failures due to increased thermal stresses and distortion [1]. Students can then use this knowledge to change build orientation to avoid thin walls. Fig. 9 shows a part with highlighted thin walls.

**E. Slicing of STL Files**

The next step after design analysis in the AM workflow is to export an STL file of the part in the required build orientation and slice it to generate slice contours, which are given as inputs to the AM machine to deposit the material to build the part. As a part of a class assignment, the students were asked to create their own slicing algorithm and visualize the sliced STL layers

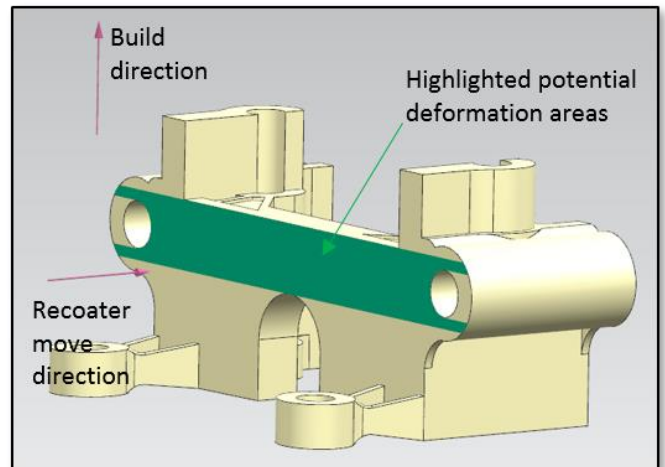


Figure 8 Highlighted potential recoater arm collision areas with sharp edges of the part



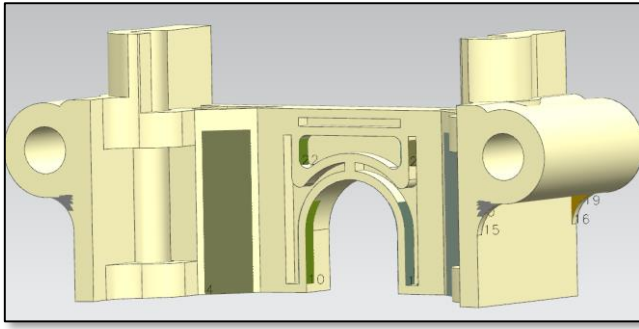


Figure 9 Highlighted thin wall areas within the part.

using MATLAB. To overcome the inaccuracies involved with an STL file, a Direct CAD geometry slicer [9] has been developed and integrated within the NX environment. The students use this module and compared the chordal error [10] for STL file with the errors obtained with the direct sliced file. Fig.10 (a) shows the test part and Fig. 10(b) shows the slices developed using the Direct CAD Slicer.

#### F. Sintering Area and Build Time

Time and material consumption are important parameters to be considered before building any part. An NX module that calculates layer-by-layer as well as total build time based on sintering areas / hatch pattern for a given build orientation was utilized by students to perform build time analysis for the given part geometry. Fig. 11 shows the slicing analysis and output for sintering area.

#### G. Cusp Height

The layer-by-layer nature of AM processes introduce a staircase effect during the build that leads to a part surface error known as cusp height [11] as shown in Fig 12(a).

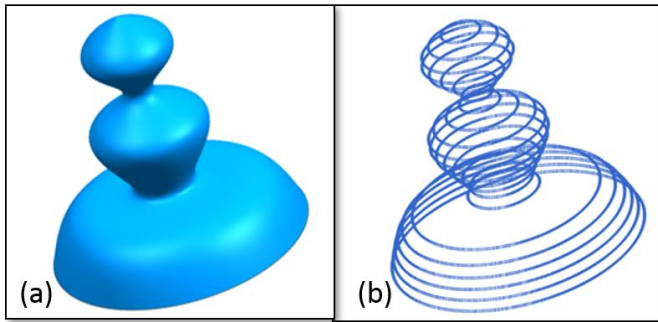


Figure 10 (a) Solid Geometry and (b) Direct Slicer Output (adapted from Vaidya and Anand [9])

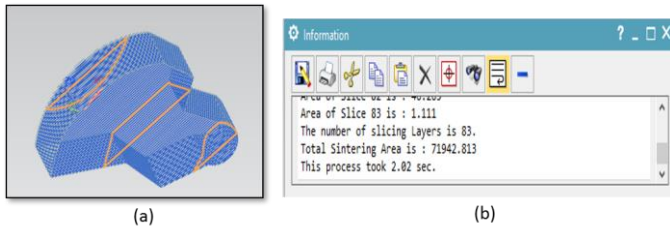


Figure 11 (a) Slicing contours. (b) Output for sintering area

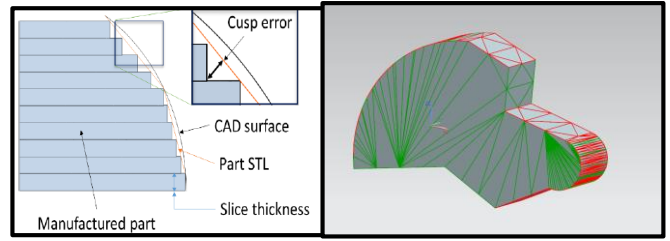


Figure 12 (a) Cusp Error and (b) Highlighted facets with cusp error greater than threshold value

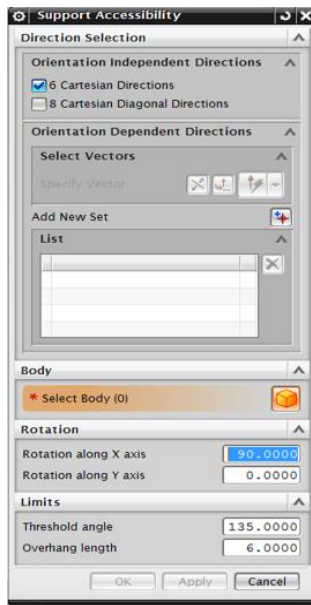
To enable the student to calculate such part surface errors, a cusp height calculation module has been developed within NX. This tool highlights the facets of a solid object that exceed the threshold value for cusp height error and helps students to understand the errors associated with AM for a given layer thickness as shown in Fig. 12 (b).

#### H. Post-Processing Simulation Using Accessibility Tool

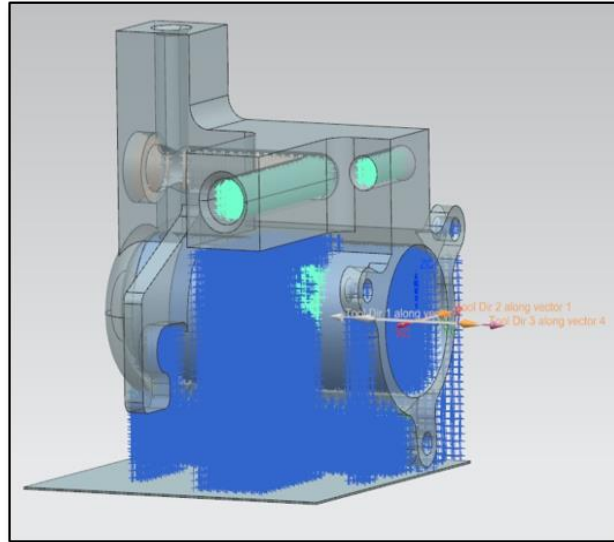
Support structures are sacrificial elements in a part manufactured with metal additive manufacturing technologies. These elements are required to provide supports to overhanging geometric features during the build and therefore can be removed once the build process is completed. The geometric build orientation of the part could be optimized to minimize the need for supports or an optimum sequence of steps for tool approach directions could be evaluated for each orientation to remove the support structures in an efficient manner. The latter problem is referred as accessibility analysis of support structures [7]. Solving this problem typically requires either intuitive feedback of an experienced user setting up the build or multiple physical trials to pinpoint an optimum build orientation and plan for support removal. The accessibility tool developed within X provides a virtual method of performing these trials and suggesting optimum sequence of tool approach directions for removing support structures. It also feeds in inputs to the overall Producibility Index evaluation tool to analyze support accessibility in all orientations for identifying the best build orientations. This leads to significant savings in optimizing post processing time and effort for support removal. For complex geometries. The accessibility analysis algorithms were implemented inside NX environment using a user-friendly GUI based toolset as shown in Fig. 13 (a). The tool generates different tool approach directions with different regions of supports coded in different colors to provide a visual aid of understanding support removal efforts as shown in Fig. 13 (b). This toolset will enable students to understand the concept of support accessibility for AM by allowing them to analyze different results based on different sets of user inputs for build orientations. This virtual verification could help students to be more prepared to sustainably 3D print parts on an AM machine setup. Fig. 14 summaries the output of the accessibility module.

## IV. CONCLUSIONS AND FUTURE SCOPE

This paper presents a systematic approach to identify design attributes and associated processing problems in additive manufacturing within a Siemens NX environment. The tools



(a)



(b)

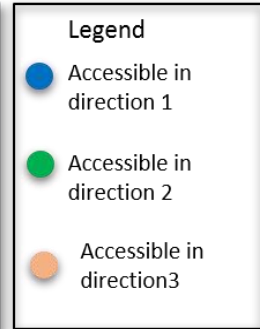


Figure 13 (a) GUI for choosing tool directions (b) Output showing accessible support points in different colors with Legend

that have been integrated provide a visual insight to the students for understanding and mitigating AM design and build problems. To unlock the full potential of AM processes, topology optimization and lattice structures can be leveraged to light weight a given part design as a part of AM work flow. The planned syllabus for students will include students optimizing the given part geometry using modules for topology optimization and lattices that will be eventually integrated with the existing toolset in the Siemens NX environment.

Another planned work is to combine the developed virtual toolset for AM with other technologies such as big data, IOT, Cloud computing etc. and integrate them as a part of the Industry

4.0 framework with the help of Siemens MindSphere cloud computing environment.

#### ACKNOWLEDGMENT

The authors would like to acknowledge Digital Manufacturing and Design Innovation Institute (DMDII) for supporting some of this work. We would also like to thank Siemens PLM for providing the appropriate software and support for building these tools.

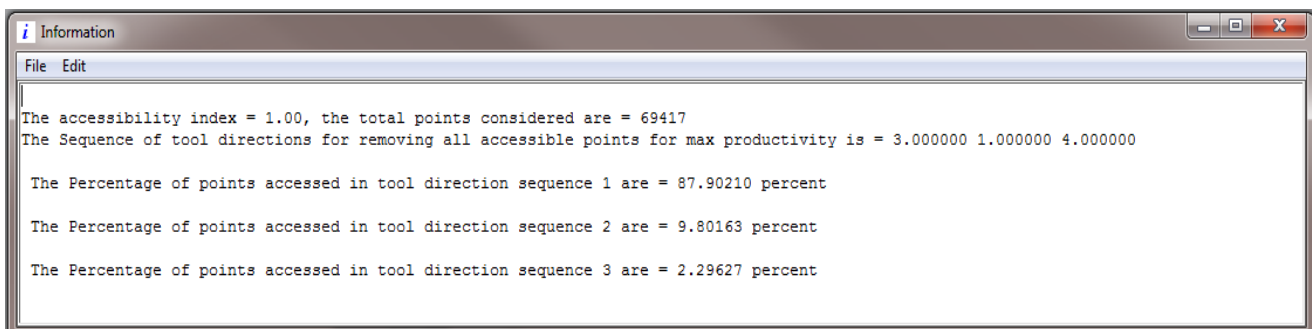


Figure 14 Accessibility output

## REFERENCES

- [1] Clijsters, S.; Craeghs, T.; Moesen, M.; Kruth, J.-P.: Optimization of thin wall structures in SLM. In: Fraunhofer Additive Manufacturing Alliance (Editor): Direct Digital Manufacturing Conference 2012. Berlin, March 14th-15th, 2012
- [2] Chowdhury Sushmit, Mhapsekar Kunal, and Sam Anand, "Part Build Orientation Optimization and Neural Network-Based Geometry Compensation for Additive Manufacturing Process." *Journal of Manufacturing Science and Engineering* Vol. 140 No. 3 (2017): pp. 1-15. DOI [10.1115/1.4038293](https://doi.org/10.1115/1.4038293)
- [3] Kruth J. P., Vanderbroucke B., J. Van Vaerenbergh, P. Mercelis. "Benchmarking of Different SLS/SLM Processes as Rapid Manufacturing Techniques." *Proceedings of the International Conference of Polymers and Moulds Innovations* pp: 1-7. Gent, Belgium, April 20-23, 2005
- [4] Samperi Matthew T. "Development of Design Guidelines for Metal Additive Manufacturing and Process Selection." M.S. Thesis. Pennsylvania State University, PA.2014.URL.<https://etda.libraries.psu.edu/catalog/21832>
- [5] Guido Adam A.O., and Detmar Zimmer, "Design for Additive Manufacturing – Element Transitions and Aggregated Structures." *CIRP Journal of Manufacturing Science and Technology* Vol. 7, No. 1 (2014): pp. 20-28. DOI [10.1016/j.cirpj.2013.10.001](https://doi.org/10.1016/j.cirpj.2013.10.001)
- [6] Jacobson, Daniel M. and G. Vann Bennett. "Practical Issues in the Application of Direct Metal Laser Sintering." *Proceedings of the Solid Freeform Fabrication Symposium* pp: 728-739 Austin TX, 2006.
- [7] Samant Rutuja, Ranjan Rajit, Mhapsekar Kunal, and Sam Anand, "Octree Data Structure for Support Accessibility and Removal Analysis in Additive Manufacturing." *Additive Manufacturing* Vol. 22 (2018): pp. 618-633. DOI [10.1016/j.addma.2018.05.031](https://doi.org/10.1016/j.addma.2018.05.031)
- [8] Ranjan Rajit, Samant Rutuja, and Sam Anand, "Integration of Design for Manufacturing Methods with Topology Optimization in Additive Manufacturing." *Journal of Manufacturing Science and Engineering* Vol. 139 No. 6 (2017): pp. 061007 (1-14). DOI [10.1115/1.4035216](https://doi.org/10.1115/1.4035216)
- [9] Vaidya Rohit, and Sam Anand, "Image Processing Assisted Tools for Pre- and Post- Processing Operations in Additive Manufacturing." *Proceeding of the 44<sup>th</sup> North American Manufacturing Research Conference* pp: 958-973. Blacksburg, VA, 2016
- [10] Navangul Gaurav, Paul Ratnadeep, and Sam Anand, "Error Minimization in Layered Manufacturing Parts by Stereolithography File Modification Using a Vertex Translation Algorithm." *Journal of Manufacturing Science and Engineering* Vol. 135 No. 3 (2013): pp. 031006 (1-13). DOI [10.1115/1.4024035](https://doi.org/10.1115/1.4024035)
- [11] Choi S.H., and Samavedam S., "Modelling and optimisation of rapid prototyping." *Journal of Computers in Industry* Vol. 47 No. 1 (2002): pp. 39-53. DOI [10.1016/S0166-3615\(01\)00140-3](https://doi.org/10.1016/S0166-3615(01)00140-3)