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DMDII
a UI LABS Collaboration
DIGITIZING AMERICAN MANUFACTURING

DMDII FINAL PROJECT REPORT

ELASTIC CLOUD BASED MAKE	
Project Team Lead	GE Global Research & DMDII
Project Designation	14-01-10
UI LABS Contract Number	0220150009
Project Participants	Pennsylvania State University Advanced Research Laboratory Rolls Royce Western Illinois University / Quad City Manufacturing Lab Iowa State University Oregon State University Rochester Institute of Technology Northwestern University
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I. EXECUTIVE SUMMARY

The U.S. suffered a decline in manufacturing over the past decade. Key to reversal will be greatly expanded efforts to support competitiveness of small and medium-sized enterprises (SMEs). Unfortunately, SMEs lag larger manufacturers in adopting new technologies. As noted in the 2010 Council on Competitiveness report, a key area where SMEs within the U.S. face an important challenge is in the adoption of information technology—particularly advanced modeling, simulation, and analysis tools (MS&A)—where their critical role in manufacturing competitiveness is becoming more important. Through the Defense Advanced Research Projects Agency (DARPA) Advanced Vehicle Make (AVM) Tool Integration project, this project was looking to directly address these technical challenges to SMEs through the enablement of access to AVM MS&A tools via the Digital Manufacturing and Design Innovation Institute (DMDII)-Digital Marketplace Commons (DMC). By transitioning the iFAB Tools into the DMC, this project was striving to establish a framework for companies, particularly SMEs, to gain access to the powerful MS&A tools developed under the previous DARPA AVM program. Additionally, resources were allocated to the development of educational materials that will be disseminated through academic courses and SME online training modules.

More specifically this project was set up to deliver the following:

- Integrate a suite of mature manufacturability assessment and flexible manufacturing configuration AVM tools into the DMDII DMC to realize a break-through platform providing key tools to the commercial market place.
- Provide an end-to-end demonstration of mature AVM tools delivered as services by the DMC spanning key areas of the design to manufacturing process continuum.
- Execute the project using a diverse team of SMEs, large-scale industrial manufacturers and academic institutions to show the depth and breadth of the AVM tools through the DMC.
- Demonstrate how the resulting software solution, upon successful completion of the project, will be useful to other manufacturing companies beyond those involved directly in the project, and provide notional use case examples of how the software can be used commercially.

DMDII along with its members and Executive Committee explored many potential applications of the DMC platform and evaluated its corresponding software development business model in 2017. That analysis showed that DMC's DOME-based architecture involves significantly higher development and maintenance costs as compared to more modern micro web services and container-based approaches. The consensus feedback across DMDII partners was that the DMC as originally conceived will not drive a significant ROI for their organizations and will be too costly to successfully scale. As a result, DMDII shelved its work on the DOME-based platform as well as any application that was planning to integrate within it. We then transitioned efforts and actively pursued new lightweight, commonly used architectural models that can more cost-effectively support specific cloud-based applications on an as-needed basis.

However, there was much work done to further develop and generate training for a handful of AVM Technologies. The work completed by each of the project participants is summarized in the sections below.

II. IOWA STATE UNIVERSITY

In this project, the ISU team developed application programming interfaces (APIs) for machinability and castability. The APIs were intended to create services that would be exposed through the DMC. The AVM tools transitioned were MachiningANA and castingANA. ISU was involved in the process of manufacturability assessments for orphaned parts, performed using transitioned AVM tools.

III. NORTHWESTERN

The Northwestern University team was tasked with Methodology and Content Development for Education and Training of Customers for AVM Modules/Use Cases, with a focus on student education. In particular, the Northwestern effort included the following:

- Develop educational content for background
- Used available versions of the iFab software.
- We interfaced with the PSU, ISU, and OSU teams during the project regarding tool usage
- and getting the latest versions of the tools available.
- Developed videos showing how to install and use the software.
- Note that at the final meeting on September 14, 2017, we were informed that the iFab
- toolset would not be integrated into the DMC, and therefore there would not be a user
- interface for most of the tools. In addition, new versions of the toolset were presented
- which were not available to us when we were developing our training material

Using the information and tools provided, the NU team developed training modules for the project. The educational content consists of background information, software demonstration and examples.

1) iFab and Cost Analysis

The iFAB suite contained a cost analysis module that employed a plug-in called MAAT (from PSU) within PTC Creo. The Northwestern team thus developed educational worksheets, documentation, walkthrough videos, and lecture slides on the download, installation, purpose, and use of PTC Creo, MAAT, and iFAB. Three one-hour lectures were created in the series to be part of an ECBM short course.

The first lecture introduces the concept of cost analysis within the context of design and manufacturing. The second lecture introduces iFAB, including how it used, and why it is useful for design and manufacturing. The final lecture provides hands-on examples of iFAB use with example assembly files made by the Northwestern team. The use of the MAAT software is extensively detailed in this lecture to prepare students for their future analysis of their own designs with the tool.

2) Automated Manufacturability Analysis (ANA)

The Automated Manufacturability Analysis Software (ANA) provide automated analysis of a part's manufacturability in machining and casting process. It composed two separate software tools: Machining ANA and Casting ANA. ANA directly uses CAD model in STL format for analysis.

For machining ANA, with any given CAD geometry, the output will provide: 1) visibility 2) reachability 3) machinability and 4) setup complexity. Casting ANA gives analysis of 1) Large areas of constant cross section 2) Isolated heavy section 3) visibility of casting surfaces from primary axis and 4) features that will likely require cores. However, at the time of project the casting ANA is still in the early stage of development. Modification might be done for an easier usage.
The ANA modules contains three sets of PowerPoint slides: 1) Machining and Casting Basic: This module provides basics in machining and casting process to give user a rough idea on both manufacturing processes. 2) What is ANA: This module introduces both ANA tool packages and what does ANA do. It also provides some sample results of both ANA packages so users can familiar themselves with ANA. 3) How to install ANA and example run: This module introduces how to carry out an analysis using machining ANA. The casting ANA was still in its rudiment so it is not included in module 3.

3) Assembly Planning

The Northwestern team developed presentations to teach students with underlying concepts related to the AAP assembly planning software package, such as assembly, assembly planning, automation and its importance. The installation procedure and different software and tools needed for it were explained. Details of the process for proper execution of software is being discussed. In this section, various concepts such as software file system, AAP options and physical meaning of them, part properties, and fastener features are being clarified. Moreover, the visualization tools and the interpretation of them are be discussed with student through in-class practices to give students hands-on experience of working with this software. Also, it is noteworthy that a series of step-by-step tutorial videos were being developed to demonstrate the installation, operation, and visualization procedures for AAP.

Second effort of northwestern team was to provide constant feedback to developer team in order to improve the software and fix the bugs happened working on different platforms and software packages. In this part, we designed multiple use cases to check the capability of AAP software and its compatibility with different operating systems as well as CAD inputs.

The iFab toolset was presented to undergraduate and graduate by Mark Fleming in an optimization conference (insert title of presentation). In addition, there were discussions with the professors for the senior design projects. Unfortunately, the tools were never finalized to the point that they would be usable by students.

IV. OREGON STATE UNIVERSITY

Building on previous DARPA AVM work and grant DMDII-14-02-04, the team at Oregon State University worked to make their Automated Assembly Planning (AAP) approach available as a web-accessible tool. Under the original contractual details with General Electric, OSU was to provide API functionality so that the work could be incorporated into the Digital Manufacturing Commons. Given changes through the course of the work, the Oregon State team attempted to independently develop with web functionality. The work funded under this grant could be seen as having a higher TRL than DMDII-14-02-04, and as such, the final reporting details for that project detail much of the intellectual merit and potential industry impact.

The resulting software that was developed can be accessed at: https://github.com/DesignEngrLab/AutomatedAssemblyPlanner. The goal is to accept, as input, a set of shape files where each shape is a component within the assembly positioned relative to one another in a global coordinate frame. The shapes can be in STL, PLY, 3MF or AMF file formats. The output for the tool is a single plan created as an .xml file which describes a "treequence". A treequence (portmanteau of tree and sequence) is an assembly tree showing what parts come together in a particular order. Given the timing associated with the actions and the accommodation for parallel assembly steps the treequence provides details of how and when to build parts of the system. This treequence is not particularly user-friendly. So, an external visualization has been created which shows the tree and an

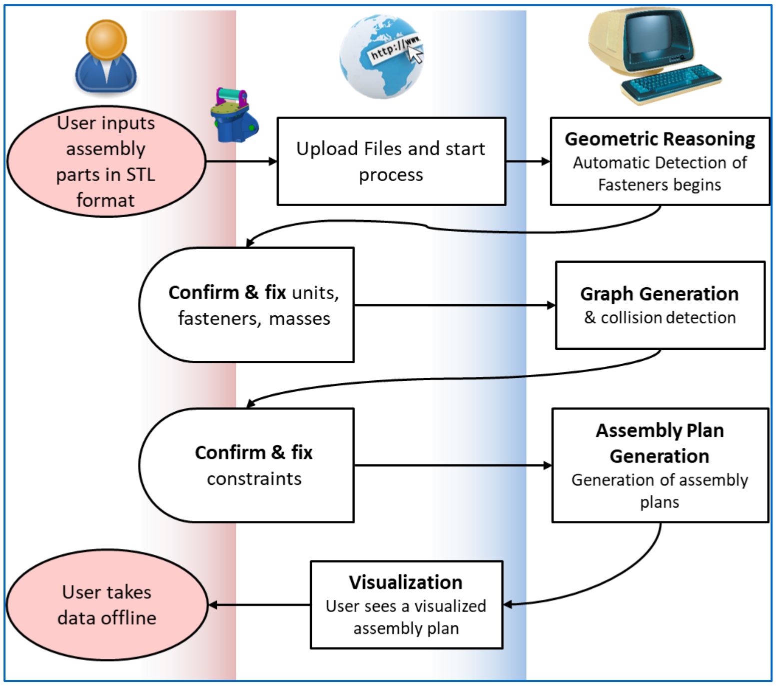


Figure 1: A flowchart showing the user-interactions intertwined with the computation that is performs.

animation of the assembly process.

Given the complexity of steps shown in Figure 1, a web-based wizard is intended to lead the user through the steps of the process.

1) System Requirements

In the current implementation, the tool is required to be run locally. The software was predominately written in C# (Microsoft .NET language). The recent work within this project was written in JavaScript as the tool was intended to be accessed from a browser and run remotely.

2) System Architecture

There are three components to the work:

1. A set of webpages written in JavaScript that interact with the user and send data files to a local server.

2. A dynamic-link library, “AutomatedAssemblyPlannerLibrary.dll” that includes all the main functionality of the tool.
3. A set of executables that move information from the user through to the aforementioned library.

3) Features & Attributes

The work takes advantage of artificial intelligence to reason about the included shape files. This is necessary since no constraint information is automatically stored in the data. Through a series of dialogs, the tool determines information needed to estimate time and stability calculations for finding the best assembly plan.

4) Modes of Operation

The tool can be used in a data-in / data-out sense, via the web-tool, or as a plug-in in the virtual reality software, IC.IDO. As indicated in Figure 2, the user is queried an additional two times following the upload of shape files. It is possible that their responses be defined as data, but in all likelihood some presentation of the three-dimensional assembly will be needed. Hence, the desire to develop a “wizard” in HTML5 to extract this information.

5) Software Development Documentation/Design Document

All software documentation and code can be found at the github link:
https://github.com/DesignEngrLab/AutomatedAssemblyPlanner

IV. PENNSYLVANIA STATE UNIVERSITY

Over the course of the ECBM project, several modules were further developed by PSU ARL and delivered to DMDII. The following sections describe the contents of each of the modules and their purpose. The 14-01-10 technical deliverables include several software packages and brief user instructions.

DMDII Tech Showcase

This compilation of utilities was prepared for the technology showcase and demonstrated two use cases: conceptual manufacturing analysis and detailed manufacturing analysis. The capabilities were encapsulated in a DOME model and entered into the Digital Manufacturing Commons for a demonstration to the DMDII Technical community.

The DMDII Tech Showcase files are a reference implementation for the Digital Manufacturing Commons (DMC) integration and includes 3 software tools. Included in the package is a welding cost estimating tool (Welding DOME), a manufacturing analysis tool for early concept design analysis (PML Conceptual Costing), and a manufacturability analysis tool used to assess designs that are nearing completion (iFAB Foundry DOME Model). Each of these tools was demonstrated during a Technology Showcase meeting hosted by DMDII. Each of the applications described below are comprised of a model (application/capability), DOME interfaces, and a DOME model.

Welding DOME Model

The *Welding Dome* folder contains the reference implementation for a weld cost estimating tool developed during the DARPA AVM program. The core application was developed in Java and includes a Microsoft Excel configuration file for updating costs for other organizations.

PML Conceptual Costing

The *PML Conceptual Costing* folder contains the Python conceptual level analysis model/application and the DOME model implementation. This tool provides rough cost and lead time estimates for designs in their early stages for designers to get an idea of the manufacturing processes that might be used to produce the components.

iFAB Foundry DOME Model

The final analysis application included in the technology showcase deliverable is a DOME implementation of the Manufacturability Analysis and Assessment tool developed in the DARPA AVM Program. For details on the overall application functions, please see the General Manufacturability Assessment Section. This package contains all of the models and interfaces for passing a design through the DMC to the analysis servers hosted at Penn State to perform a detailed manufacturability analysis for the given designs. Note that this implementation requires setting up an analysis server and includes a detailed cost analysis performed by the aPriori commercial costing engine, and a license for aPriori bulk costing is also required.

MAAT and Cost Analysis Cloud

The *Manufacturing Augmentation and Analysis Tool* (MAAT) and *Cost Analysis Cloud* folder represents the non-DMC implementation of the MAAT and Detailed Cost Analysis Server. The folder contains installation packages and user instructions for installing MAAT, the server setup and scripts, the rails application (web interface for receiving designs and presenting feedback to the user outside of the Creo Plug-in version), and the source code for the setup for replication outside of the Penn State system.

Please refer to the General Manufacturability Assessment Section in the appendix for discussion of the assessment approach. Note that this implementation includes the aPriori commercial costing engine, therefore a license for aPriori bulk costing is also required.

NXMAAT Plugin Installer

The *NXMAAT Plug-in Installer*, is the install package for the Siemens NX version of the Manufacturing Analysis Augmentation Tool (MAAT). The functions are very similar to the Creo Plug-in, but instead work with the NX CAD Package.

PMLALL

The PMLALL is the final version of the Conceptual Manufacturability Analysis application. The development language is in Python and the folder contains the compiled application and source versions of the tool. The tool includes an interface for users to define alternative vendors with specific capabilities defined in the Process Modeling Language. The user is able to submit a very rough/early stage design and the tool will present the user with alternative vendors for various manufacturing processes and estimates the cost and lead time based on the standard process steps for each manufacturing process.

Scheduler

The Scheduler application is a relatively simple scheduling application that was extracted from the main Manufacturability Analysis tools described in the Appendix. This file contains the compiled application and source versions of the tool. It is anticipated that the tool would be the starting point for DMDII members to enhance and integrate with current applications, however the tool can be used in stand-alone mode given the appropriate inputs.

Wire-Harness

The Wire-Harness application is a Java graphical user interface developed during the DARPA AVM program to provide cost and lead time estimates for wire harness manufacturing. The file contains both the compiled applicationand source code and should be used as a stand-alone application to predict costs for wire harnesses during the design phase.

Appendix

General Manufacturability Assessment

Under the DARPA AVM program, ARL Penn State developed, deployed and tested a Manufacturability Assessment Software System that rapidly assessed designs to determine manufacturing feasibility, cost and lead time. The system was capable of analyzing designs of varying complexity in terms of number of components (from 1 to ~1000) and types of components (purchased, machined, plate, pipe, assemblies, etc.). The system was deployed on a small hardware cluster (100 nodes) and was accessed from multiple designers using one of two interfaces, a service oriented interface and a direct connect interface. Testing of the system was performed both internally as well as externally through the Gamma Testing phase of the AVM program where five teams created designs of infantry fighting vehicle hulls and submitted them to the system for analysis and feedback. The system is comprised of several analysis software applications that are seamlessly integrated to provide general manufacturability analysis and feedback to the design teams. Figure 2 shows the overall process flow for the Manufacturability Assessment Software System.

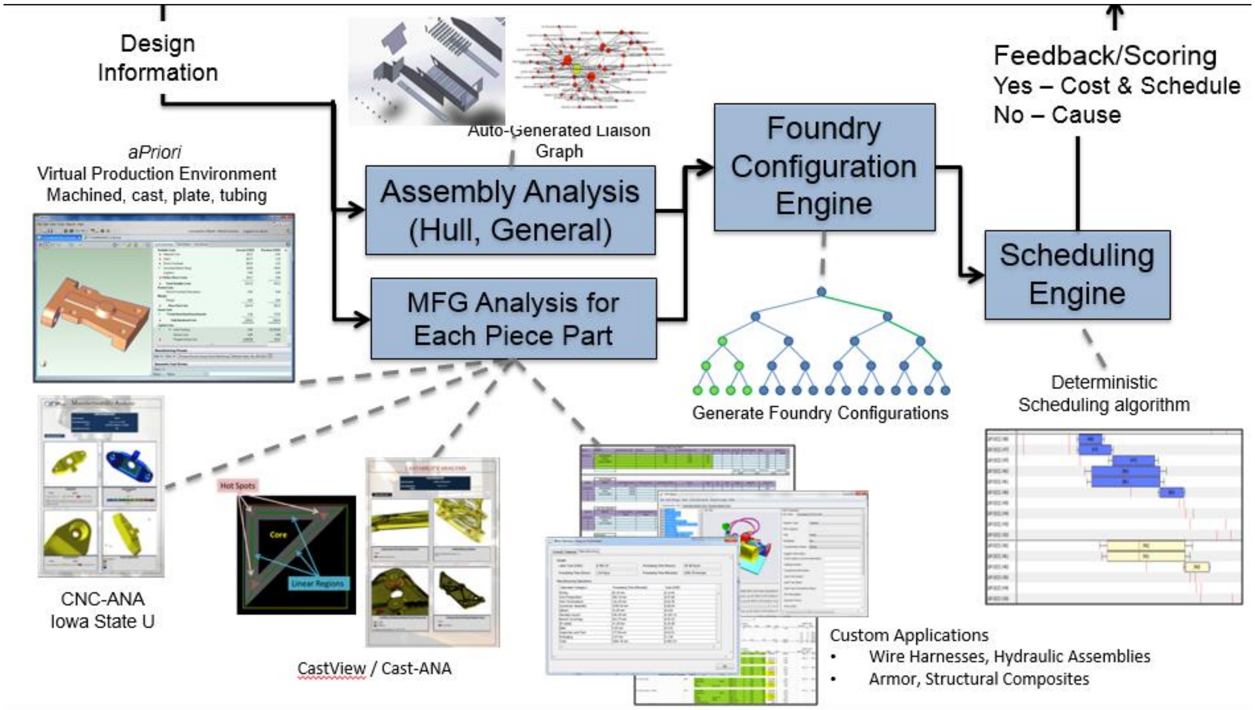


Figure 2: Manufacturability Assessment Software System Process Flow Diagram

Upon receipt of a design, the system decomposes the design files (CAD STEP AP203 and Manufacturing Models XML files) into data packages for Assembly Analysis and Manufactured Piece Part Analysis. These two analysis operations occur in parallel. Once the parts and assembly have been analyzed, the data package moves to the Foundry Configuration Engine. The data package at this point in the process is comprised with notional resource requirements for each operation determined in the analysis phase. The Foundry configuration engine queries the Manufacturing Model Library for alternative resources for those operations and develops a graph of all possible resource allocations and routings. The scheduling engine then performs a resource-constrained project scheduling algorithm to determine the overall makespan for the submitted design. The costs found in the analysis phase are rolled up and the makespan is calculated for each foundry configuration. This results in many alternative process plans with associated costs and lead time. The returned result is the cost and lead time of the mid-point of the Pareto Front, i.e. cost and lead time are equally weighted.

Design Decomposition

Designs are submitted to the ARL Penn State iFAB Foundry Manufacturability Assessment System as models or collections of models. The models include a geometric representation (CAD Model) of the design in addition to information about the components that are to be manufactured. This information includes: material, surface finish, gross geometric dimensioning and tolerances, in addition to other potential product manufacturing information (PMI), i.e. part class, general manufacturing processes.

The model decomposition engine is responsible for decomposing the design submitted through the interface into operable pieces of geometrical and informational objects. This will include decomposing the design into graph structures as well as individual part representations.

Assembly Analysis

The design domain considered in the AVM Program was Infantry Fighting Vehicles. These vehicles are comprised of a monocoque hull structure with a drive train (ground and aquatic) and all accompanying support systems such as cooling and driver controls. In an effort to reduce the complexity of the Assembly Analysis algorithms, the iFAB Foundry team developed two assembly analysis modules, one for the hull structures and one for general assembly components.

Hull Assembly Planning

The Hull Assembly Planning module employs a case-based reasoning approach in conjunction with a geometric reasoning approach to develop assembly sequences for hull structures. Cases for logical subassemblies were developed using hull manufacturing cases from the shipbuilding industry and ground vehicle manufacturer subject matter experts. The general flow for this module follows the flow presented in Figure 3.

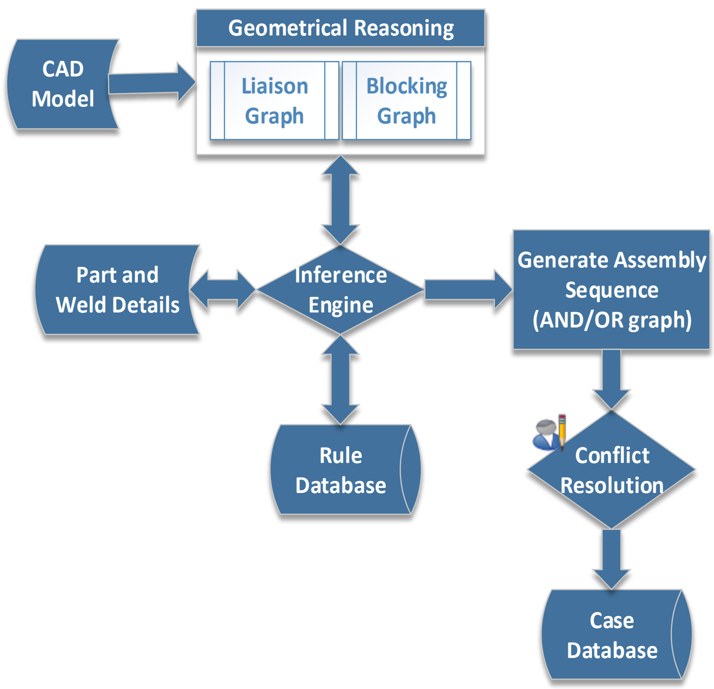


Figure 3: Hull Assembly Planning Module Flowchart

The output of the Hull Assembly Planning Module is a list of feasible sequences that are first passed to a weld costing package and then to the Foundry Configuration Engine for further processing.

General Assembly Planning

A reverse disassembly-sequencing approach is used in the General Assembly Planning module. This involves inferring a sequence of actions that transforms an assembly to an unassembled state - consisting of isolated components. The advantage of starting from an assembled state is that it reduces the search space due to inherent constraints (degrees of freedom) on the mobility of individual components. The method employs a geometric reasoning technique that first computes the nondirectional blocking graph (NDBG), then computes disassembly sequence. Figure 4 shows a diagram of the implemented approach.

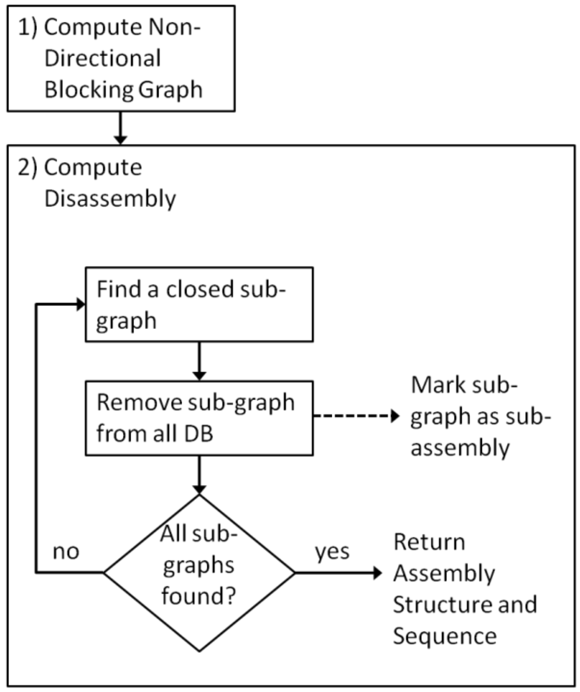


Figure 4: Assembly Structure and Sequence Generation Algorithm

Similar to the Hull Assembly Analysis, the result of this module is a list of feasible sequences holding the hull component fixed and fully assembled. The list is first passed to the costing routines and then on to the Foundry Configuration Engine for further processing.

Assembly Cost and Manufacturing Time Analysis

The iFAB Manufacturability Assessment System supports three types of join types for assembly; 1) welding, 2) mechanical fastening, 3) bonded or glued. The assembly planning modules described earlier identify feasible assembly sequences which are passed to the costing analyses for each of the supported join types.

Welding

Weld cost and lead time is affected by both the design of the weld and the process chosen to create the weld. Although there are many welding processes available, Gas Metal Arc Welding (GMAW) is one of the most versatile and, as such is the only fully supported welding process in the system.

The direct costs of GMAW welding are labor, materials, and energy. The materials include the welding wire and the shielding gas. Additionally, welding operations require supporting operations such as engineering and maintenance, as well as equipment and shelter. The support items can be considered overhead costs and the model employs an overhead multiplier. The hourly cost for labor was fully burdened with these overhead costs.

In order to develop the time and cost for a given weld, the actual amount of material required by the geometry of the weld is used. For the weld cost model, a few specific standard weld joint designs were input with a limited number of plate thicknesses. These weld joint designs were butt, tee, corner, lap, and edge. The model also takes into account whether these joints are one or two sided. This information enabled the calculation of the cross sectional area of the weld for a given width of the base material. Lastly, the total length of the welded joint was input. By multiplying the cubic foot of welded joint by the deposition rate in cubic feet per hour, the number of hours required to complete a joint was estimated. Cost is estimated by multiplying the hours by a labor rate.

Mechanical Fastening

Similar to welding, the assessment system contains a cost model for mechanical fastening (bolted, blind bolted, press fit, snap fit, etc.). This model not only considers the attachment time associated with connecting parts, but also the potentially complicated and time consuming material handling required with assembly of large components. The models were based on industry standard estimates and can be refined and tailored to a new organization with minimal effort.

Custom Manufactured Components

As the name indicates, custom manufactured components are components that are not sold in catalogs and must be manufactured using one or more manufacturing processes. The iFAB Manufacturability Assessment System is capable of analyzing machined, cast, plate, and pipe/bar with a variety of additional coatings, plating or painting. Several analysis applications are employed for this assessment that provide a range of feedback from detailed model views that highlight areas that can/should be modified to costing analysis to costing and feasibility assessment. Each of these applications is described in the following subsections.

aPriori

aPriori was one of the primary manufacturing analysis tools integrated within the iFAB IA during the AVM program. The core of aPriori's product is a feature-based analysis capability through geometric reasoning of a CAD input file. Analyzing the CAD part, and incorporating limited manufacturing data requirements (e.g., part/process class, part material, build quantity), aPriori predicts a cost to physically manufacture each feature, assuming a specific factory/manufacturing facility's capabilities, and then totals them up to arrive at a cost prediction for a part.

In addition to aPriori's core capabilities of geometric-based cost analysis, there were two additional aspects about the software that were attractive for implementation within the iFAB Foundry Manufacturability Assessment System:

1. Virtual Production Environments
2. "Back-end" software implementation using process setup options

aPriori can be exercised either through the use of a graphical user interface (GUI) or as a server-based application. While the aPriori GUI is extremely valuable in the validation of VPEs and selective cost analysis of parts, the iFAB Manufacturability Assessment System needed to employ an implementation that would provide designers the rich manufacturability feedback that aPriori offers without requiring a desktop client installation. This is otherwise known as the "back-end" or server-based implementation of aPriori. aPriori offers two core capabilities that enabled the iFAB Foundry back-end implementation: 1) *Bulk Costing* and 2) *Process Setup Options*. These two concepts are discussed below.

<u>aPriori Bulk Costing</u>

The bulk costing capability in aPriori serves two key purposes. First, the bulk costing enables the preparation of multiple cost analysis runs to be executed by the aPriori cost model engines without the need to individually load CAD models and select basic production information, including the VPE. In addition, the bulk loader provides an efficient method of generating cost comparisons for a part produced by multiple VPEs. aPriori offers a straight-forward command line approach for bulk loading. These java-based libraries enable an implementation organization to integrate the bulk loading as part of a larger manufacturability assessment workflow. The iFAB Manufacturability Assessment System establishes pointers to the CAD model and manufacturing model data for design submissions, launches the aPriori software without the client GUI, and obtains a standard aPriori spreadsheet report to support the overall manufacturability feedback package returned to the design submitter.

<u>aPriori Process Setup Options</u>

The use of process setup options is a way of applying changes to aPriori variables prior to a cost analysis without the direct use of the aPriori GUI. Process setup option variables are selected based on end user preference and will vary depending on the implementing organization's goals. For iFAB Foundry, process setup options were established to vary GCD-specific tolerance/surface finish requirements. For instance, back-end analysis of a machined part would require process setup options for tolerances and surfaces (based on GCD type), and hole threading. In addition, process setup options were established to select specific process routes, heat treatment processes for castings, and part coating requirements.

aPriori not only provides a cost and lead time estimate based on the manufacturing processes modeled in the VPE, it also provides specific machines and process routing information for use in the Foundry Configuration Engine.

Manufacturing Model Library

The iFAB Manufacturing Model Library (MML) provides information critical to assessing designs in terms of manufacturability. In general, the MML is comprised of process models, which define relationships between sub-processes, physical and informational objects, resources (both human and non-human), and resource models. Resource models are used to calculate performance metrics, such as cost and schedule, and ultimately define process constraints.

In the AVM program, process and resource models were developed for machining, welding, casting, general assembly, coatings (organic and inorganic), sheet and plate cutting, material handling, dimensional control, and wire harness assembly. The process and resource models, or manufacturing models, were developed using off the shelf modeling tools such as the aPriori Virtual Production Environment and through the population of templates/schemas developed by the other AVM performers. The outputs of these models are machine-readable XML representations that maintain all relationships between objects and information in the models.

Foundry Configuration Engine (for Analysis)

Foundry configuration is the process by which the manufacturing process capabilities are aligned in order for the submitted design to be built. This includes the selection of processes, process steps, and resources at each process step. During the assessment phase, alternative sequences are generated for the assembly steps and alternative machines are generated for the manufactured components. Each feasible route (sequence, resources) is used to create a graph structure with the final finish node at the top. Each leaf node represents a component in the design with a unique sequence/resource allocation. This graph structure is exemplified in Figure 5.

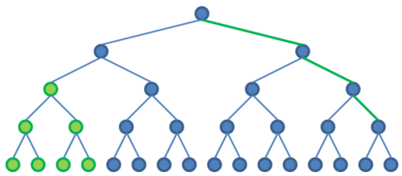


Figure 5: Foundry Configuration Graph

The foundry configuration essentially walks the graph to generate complete process plans for the given design. This results in many alternative process plans, each of which is passed to the scheduling engine to calculate the overall makespan of the design using that particular plan.

Scheduling Engine

The schedule generator is responsible for developing the production schedule and handling disturbances in the schedule during the build phase. The deterministic scheduling engine is responsible for two functions in the iFAB Foundry information system: production scheduling and production re-scheduling. The algorithm used to perform production scheduling receives a fully characterized foundry configuration, which provides the process steps, precedence constraints, resource requirements, and processing times. The purpose of the scheduling algorithm is to determine the process start and complete times on the assigned resources while considering resource availability. The availability of each resource will be defined and the information will be stored in the MML. The scheduling algorithm will query the MML for resource availability.

The algorithm creates a tree of all the processes. The root is the final activity to create the design and the branches and leaves represent the processes/activity flows required to manufacture, procure, transport, or assemble the design assembly, sub-assemblies, or components. Using the tree, the algorithms begin assigning the longest processing time activity with no predecessors to the resource in the first available time slot. This process is repeated until all activities have been assigned to the resource. Figure 6 shows the flow of the algorithm.

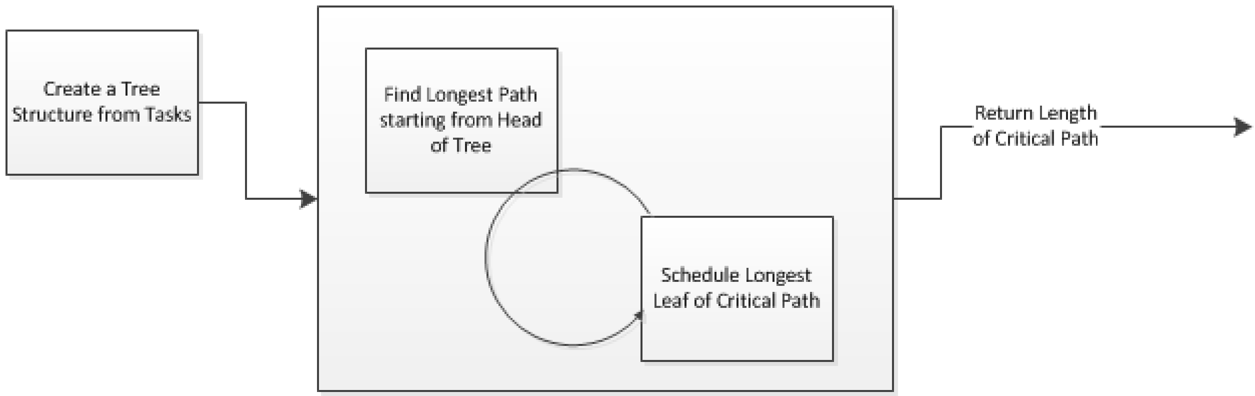


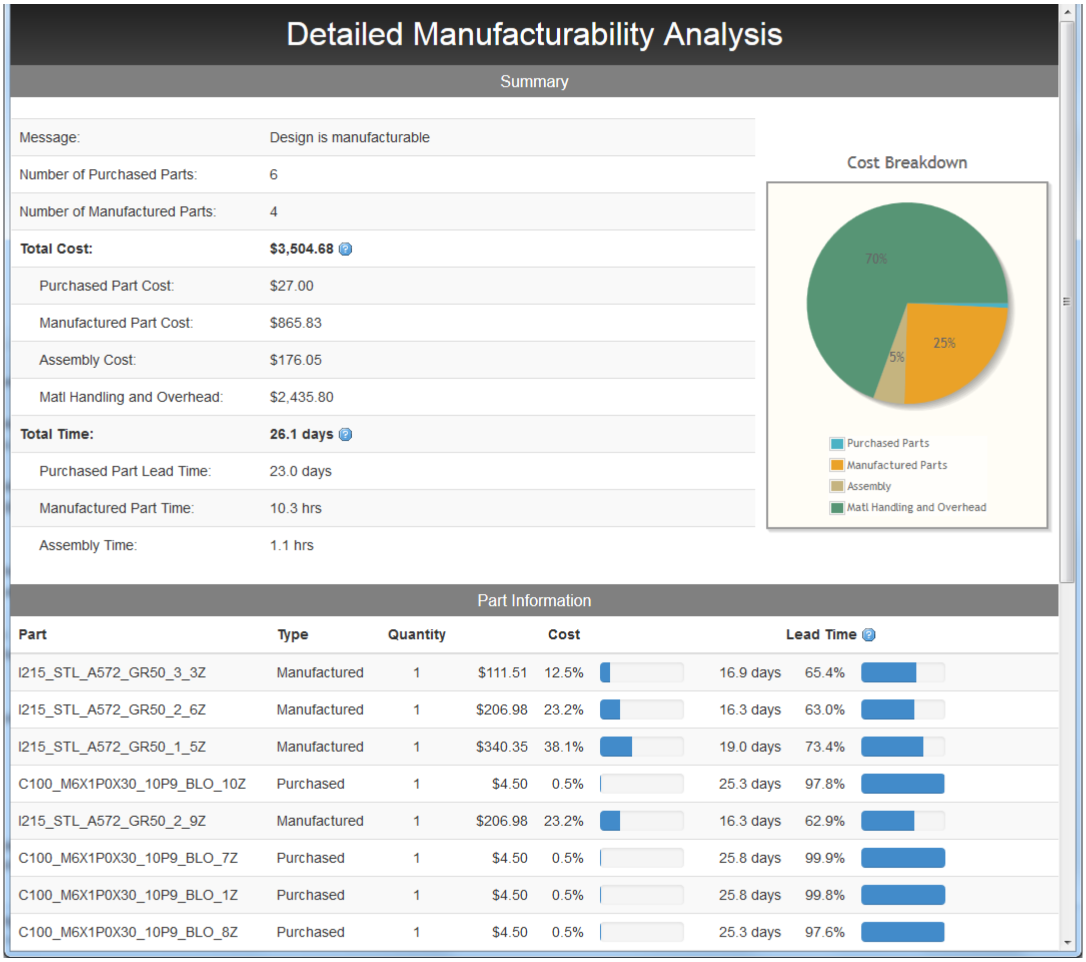
Figure 6: Deterministic Scheduling Flow Chart

The re-scheduling function of the algorithm operates in a similar manner except that the activities that have previously occurred or are currently in process are locked in time and cannot be rescheduled. More information is required regarding the alternative resources that are capable of performing the activities. This information is generated by the foundry configuration functions and passed to the algorithm through the foundry configuration object. The result from both functions of the algorithm is a detailed project schedule returned to the foundry configuration functions for display and comparison.

Feedback to Designer

The manufacturability analysis feedback generated by the iFAB Manufacturability Assessment system was presented in various mediums to the designers in the AVM FANG 1 challenge and Gamma testing. Two general types of feedback were provided to the designers; 1) cost, lead time, and manufacturing feasibility down to the piece part level, and 2) manufacturability analysis that shows the designer ways to improve the design to reduce cost and lead time or improve manufacturability.

Figure 7 shows the HTML presentation of the detailed manufacturability assessment for a full design. Detailed cost and lead time information is presented to the designer in a summary block and information about each piece part is given in the lower portion of the graphic.



Detailed Manufacturability Analysis

Summary

Message:	Design is manufacturable
Number of Purchased Parts:	6
Number of Manufactured Parts:	4
Total Cost:	**$3,504.68**
Purchased Part Cost:	$27.00
Manufactured Part Cost:	$865.83
Assembly Cost:	$176.05
Matl Handling and Overhead:	$2,435.80
Total Time:	**26.1 days**
Purchased Part Lead Time:	23.0 days
Manufactured Part Time:	10.3 hrs
Assembly Time:	1.1 hrs

Part Information

Part	Type	Quantity	Cost		Lead Time	
I215_STL_A572_GR50_3_3Z	Manufactured	1	$111.51	12.5%	16.9 days	65.4%
I215_STL_A572_GR50_2_6Z	Manufactured	1	$206.98	23.2%	16.3 days	63.0%
I215_STL_A572_GR50_1_5Z	Manufactured	1	$340.35	38.1%	19.0 days	73.4%
C100_M6X1P0X30_10P9_BLO_10Z	Purchased	1	$4.50	0.5%	25.3 days	97.8%
I215_STL_A572_GR50_2_9Z	Manufactured	1	$206.98	23.2%	16.3 days	62.9%
C100_M6X1P0X30_10P9_BLO_7Z	Purchased	1	$4.50	0.5%	25.8 days	99.9%
C100_M6X1P0X30_10P9_BLO_1Z	Purchased	1	$4.50	0.5%	25.8 days	99.8%
C100_M6X1P0X30_10P9_BLO_8Z	Purchased	1	$4.50	0.5%	25.3 days	97.6%

Figure 7: HTML Visualization of the Feedback

A lighter version of the feedback is presented in textual form with less detail about the individual components in Figure 8. The textual feedback mechanism was implemented in the Creo plugin developed to directly interface with the assessment system.

Cost ($) = 2244.6

Time (days) = 19.2

Manufacturing Cost ($) = 1175.7
- Manufacturing Labor Cost = 993.0
- Manufacturing Material Cost = 41.4
- Manufacturing Overhead Cost = 36.1
- Manufacturing Setup Cost = 131.8

Purchased Cost ($) = 0.0

Assembly Cost ($) = 1070.7
- Assembly Labor Cost = 837.3
- Assembly Material Cost = 233.5

Manufacturing Time (min) = 129.3
- Manufacturing Run Time (min) = 38.7
- Manufacturing Setup Time (min) = 90.6

Purchased Lead Time (day) = 0.0

Assembly Time (min) = 419.0
- Assembly Attachment Time = 417.8
- Assembly Setup Time = 1.2

Figure 8: Textual Feedback

Both of these feedback mechanisms are driven from a large data object that contains detailed analysis information about the submitted design. This data object is the final output from the system and includes information about cost, lead time, feasibility, and the processes and resources used in the analysis. It also forms the basis of the information for the Flexible Manufacturing Tools.

VI. ROCHESTER INSTITUTE OF TECHNOLOGY

For this project, RIT's role was to: 1) provide feedback to the tool designers while learning to utilize the tools, 2) develop training materials that allow a Small to Medium Enterprise company (SME) or college student to be able to utilize the tools, and 3) assist SMEs in utilizing the tools for a use case based on the idea of orphan parts (components for which there is no longer a source of supply).

The education and training modules developed by RIT had two purposes: 1) provide guides and training specific to the three tools and 2) provide manufacturing knowledge related to the tools that aid in understanding how the tools can be used as an important part of the manufacturing process. Training modules were designed to be utilized for academic integration, as well as training of SMEs. Most modules may be utilized for both cases unless noted otherwise, e.g. the Design for Assembly Module. The training modules are briefly described in Table 1.

Table 1 - Training Module Descriptions

Training Module	Purpose
iFAB Training Module	Provides an understanding of the capabilities and utilization of the iFAB costing tool
Machining ANA Module	Provides an understanding of the features that impact machinability of a component and how to utilize the Machining aspect of the ANA tool
Casting ANA	Provides a brief understanding of Die and Sand Casting, the features that impact the castability of a component, and how to utilize the casting aspect of the ANA tool
Design for Assembly (DFA) – Academic Training Module	Provides an understanding of the DFA process, including several examples of design changes and improvements through DFA. Intended for Academia.
Design for Assembly – SME Training Module	Provides a brief understanding of the DFA process, potential outcomes and further resources for DFA implementation. Intended for SMEs.
Material and Process Selection Training Module	Provides an understanding of the impacts of material and process selection on the design of a component. Intended for Academia.

1) iFAB

The iFAB tool, as delivered to RIT, is a plug-in to the Creo CAD package by PTC and requires a backend server for analysis, which was provided via accounts on a Penn State server. The plug-in collects additional information relating to materials, tolerances, surface finish, and assembly methods. This information and the model is sent to the backend server analysis. The analysis determines if the component or assembly is manufacturable, determines the optimal method of manufacture, and provides cost and lead time to make the component or assembly. It should be noted that the optimal method in the plug-in is the method which equally considers the lead time and cost when providing a solution.

The iFAB training module provides an understanding of the benefits of using the tool, step by step instructions on plug-in installation, an understanding of all menus, screens and outputs, and a series of exercises that walk the user through the process of creating and submitting jobs. The iFAB training module may be utilized for both SMEs and academia. The training material is a Microsoft PowerPoint titled “iFAB Training Module.pptx”.

2) Manufacturability Analysis

The ANA analysis tool is a standalone tool that will evaluate a component for machinability, or castability with either die or sand casting. The tool accepts STEP files and provides feedback while also allowing the comparison of product designs. The training material for the ANA tool was broken down into Machining and Casting as these operations are not typically done in the same manufacturing environment.

The two ANA training modules provide instructions on installing the tool, background information on machining or casting that will enable the user to interpret tool outputs, and a walkthrough of all tool features. The ANA training modules may be utilized by both SMEs and academia. However, in practice, SMEs that are contract manufacturers (the type of business that RIT engaged on the project) are usually supplied a design for production, so the tool may not be adopted as widely by this type of SME. The training materials consist of two Microsoft PowerPoint files titled “MachiningANA.pptx” and “CastingANA.pptx”.

3) Generic Training

The DMDII tools were created to aid in the design process. To enhance the training materials, RIT also developed generic training modules based around Design for Assembly (DFA) and Material & Process Selection. The modules provide SMEs with background information and links to resources, while also providing an entry level understanding of the concepts for the academic classroom.

a. Design for Assembly

RIT created two DFA modules, specifically tailored to SMEs and academia. For the SME training module, the benefits of the DFA process are discussed and resources for further exploration of DFA are provided. As the DFA process is extensive, actual implementation details are not included in the SME training. However, in the academic training, additional application information is included along with details. The decision to provide less details in the SME module was intentional, as the learning objectives focus on improving SMEs’ high level understanding of the process. A full implementation of DFA by the SMEs would require them to be dedicated to the process and develop a DFA implementation team. The training materials consist of two Microsoft PowerPoint files titled “DFA – SME.pptx” and “DFA – EDU.pptx”.

b. Material & Process Selection

Many mechanical engineers are taught computer aided design (CAD) and some of the basics of materials and processes, but they are rarely taught the impacts of material and process selection on design. RIT viewed this project as an opportunity to develop a training module that would provide mechanical engineering students with some insight into the impacts of material and process selection. This module is a good companion to the iFAB and ANA toolsets, as those tools are designed to decrease the cycle times when evaluating designs for both manufacture and cost. The materials cover the reasons that specific materials are selected, why certain processes are used, and what they are best suited for. In addition, resources are provided for further background. This academic training module consists of a Microsoft PowerPoint file titled “Selection of Processes and Materials.pptx”.

4) Orphan Parts Use Case

The orphan parts use case was designed to provide feedback on an SME’s ability to utilize the ECBM tools to obtain faster quotes for parts that no longer have a source of supply. RIT was tasked with identifying SMEs who could quote an orphan part and would subsequently quote the part utilizing the tools.

Orphan Part Selection

GE and RIT worked to identify an orphan part that had a current sourcing problem within the military community. GE received models of three components: a marine yoke, a gear and a flywheel. The models were not created from original drawings, but were clearly created from scans of actual parts. RIT utilized the ECBM tools to evaluate the three components. At the time of the evaluation, the marine yoke was the likely candidate as both the gear and flywheel were deemed not manufacturable by the software. GE made the decision to move forward with the marine yoke, see Figure 1.

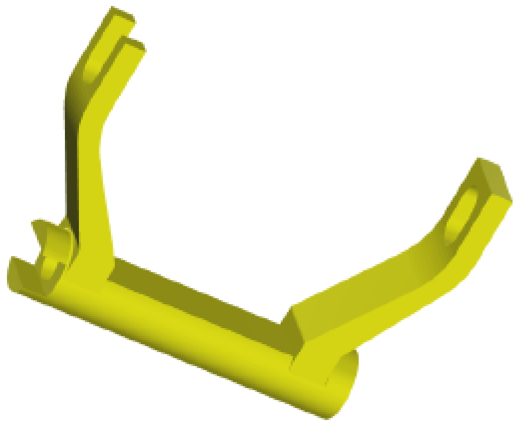


Figure 1 - Marine Yoke

Developing a Technical Data Package

Although a model was delivered to RIT, no additional engineering information about the component was provided. From the model, RIT needed to generate a Technical Data Package with enough detail to allow a SME to quote the component. RIT started the process with a basic functional analysis of the component. It was determined that the marine yoke was designed to engage a marine drive differential through the movement of a differential locking lever. As the lever was actuated, it would translate the force to slide a gear into position, thus engaging the gears in the differential. This is similar to a clutch engagement fork, as identified through internet searches (google search for "John Deere Clutch Fork").

From the design of the component and comparison to a similarly designed component found online, RIT determined that the original component was likely made from a casting. The design was reviewed with a materials engineer with significant experience in heavy machinery, who identified the most likely material as a series 30 grey cast iron. After performing a finite element analysis (FEA) to identify loads translated through the arms of the marine yoke, RIT determined the marine yoke could be machined out of 4140 alloy steel, which has a similar hardness as a series 30 grey cast iron but higher yield strength. Based on this material selection and the expected utilization of the component, RIT developed a drawing package with full dimensioning and tolerancing for the SMEs to quote. The drawings are included with the delivery of this report in a file titled "Marine Yoke – Original.pdf". The model file is included as "Marine Yoke – Original.sldprt".

Identification of SMEs

RIT reached out to multiple SMEs in New York State regarding the quoting and fabrication of the marine yoke. RIT requirements for the SME were:

1) The SME was willing to quote the component as usual

2) The SME would receive training on the iFAB tool and re-quote the component utilizing the iFAB tool
3) The SME would provide feedback on the iFAB tool, including how the tool would be utilized in their business model, what impediments to adoption they saw, and what features were missing or difficult to understand
4) The SME would track actual hours during production for comparison to the outputs of the iFAB system.

Additionally, as the goal of the program was to compare the accuracy of the tool and receive feedback on the tool, RIT allowed the SMEs to propose slight design modifications as long as they were deemed not to interfere with the functionality of the part. The original design was made for casting the component; therefore, it was not necessarily conducive to manufacture.

Of the six SMEs that RIT contacted regarding the component, three chose not to provide a quote. The remaining three SMEs were selected to move forward with training and fabrication of the marine yoke. RIT would like to acknowledge the role that Acro Industries, Arnprior Rapid Manufacturing Solutions, and CAR Industries played in evaluating the software and fabricating components as a part of this program. However, to protect company information, such as rates, etc., the companies have been randomly assigned the names: Company 1, Company 2 and Company 3 for the remainder of this report. All three of the SMEs proposed changes to the design. Two of the SMEs proposed a larger radius at the base of the arms (see Figure 2) and the third SME proposed leaving the entire underside of the arm filled in (see Figure 3). These revised models are included with this report as “Company 1 and 2.sldprt” and “Company 3.sldprt”, respectively.

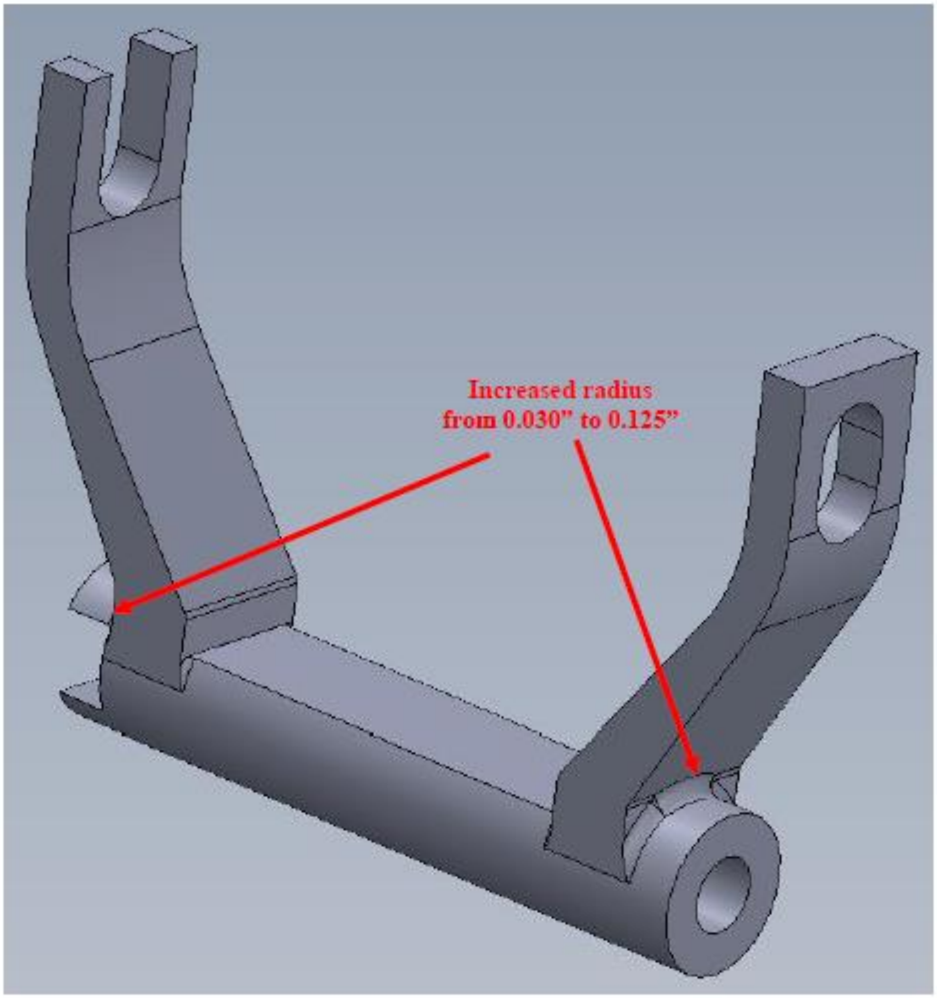


Figure 2 - Modified Design used by Company 1 and 2

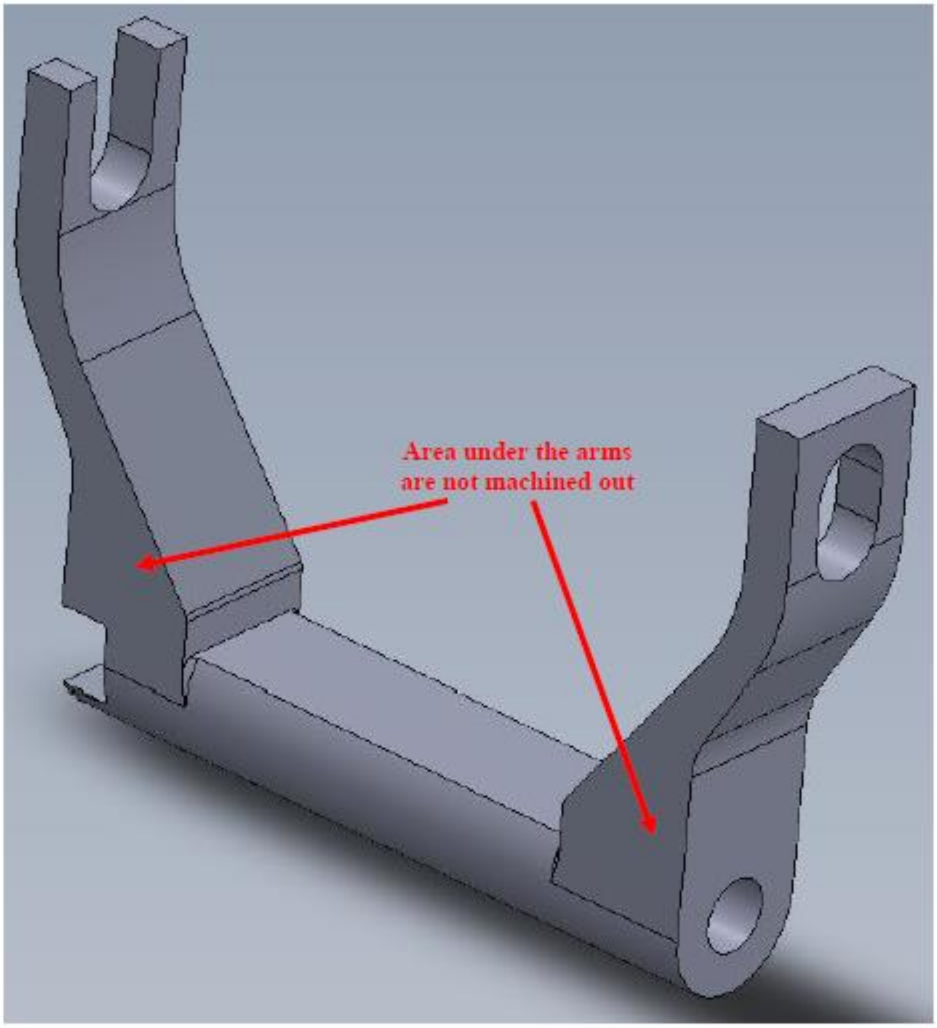


Figure 3 – Modified Design used by Company 3

5) Part Quotes and Comparison to iFAB Outputs

Initial discussions with the SMEs revealed that they would not be fabricating the two demonstration pieces the same way that they would fabricate batches of 50 pieces. Therefore, RIT made a quote request asking for three items: 1) a quote for two pieces to be fabricated, 2) a quote for a batch of 50 pieces to be compared to iFAB, and 3) a quote of engineering effort to receive training on and utilize the tool to develop an additional quote. When requesting quotes of the SMEs, RIT provided a template showing the information that should be detailed in the quote.

Subsequently, each SME was asked to fabricate two of the marine yokes in accordance with their quotes. The SMEs were asked to track their actual processing times for comparison to the iFAB outputs. However, comparisons are difficult as the two part fabrication processes did not exactly match the 50 part quotes, and further iFAB provides limited visibility into labor times associated with unit processes. An inquiry was made to Penn State regarding where specific time exists within the iFAB quote, i.e. does labor time include the load/unload and deburring time? The response from Penn State was that the system does not provide visibility into how process time estimates are generated. The iFAB software is simply a software layer that obtains additional information about product or process attributes not available in the CAD model, sends the CAD model and the additional information to a third software package called aPriori, which identifies the potential manufacturing options, and provides cost estimates. Within this process, RIT found there to be a disconnect between the terminology used by the people in industry and the tool developers.

RIT compared the results of the analysis from iFAB against each companies' quote, and also compared across the small design changes requested by each vendor. The following tables include the quote information, as well as the iFAB analysis for an assumed 50 part order of the marine yoke. Table 2 is the comparison of the Company 1 quote to iFAB results. Table 3 is the comparison of the Company 3 quote to iFAB results. Table 4 is the comparison of the Company 2 quote to the iFAB results. The iFAB outputs for both marine yoke designs are provided in Figure 4 & Figure 5.

Table 2 - Comparison of the Company 1 Quote vs. the iFAB Results

Quote line item description	Company 1 quote data	MAAT (iFAB) quote data
Material (4140 steel) – cost per piece	$16.60	$19.52
Setup		
Machine used	Mazak vertical machining center	
Machine setup - # setups	3	
Design / Engineering (programming) – Hrs. @ $85	4	
Programming and fixturing/tooling charges per piece	$23.30	
Setup time per part (HH:MM:SS)	00:09:36	1:39.40
Run time per part (HH:MM:SS)	04:25:00	00:49:00
Total time per part (HH:MM:SS)	04:34:36	02:28:40
Per piece cost (including programming and fixturing with an assumed order of 50 pieces)	$603.41	186.13

Table 3 – Comparison of the Company 3 Quote vs. the iFAB Results

Quote line item description	Company 3 quote data	MAAT (iFAB) quote data
Material (4140 steel) – cost per piece	$18.06 each	$17.04
Setup		
Machine used	Haas VF5 vertical mill	
Machine setup - # setups	5	
Design / Engineering (programming) – Hrs.	6	
Programming and fixturing/tooling charges per piece	$48.00	
Setup time per part (HH:MM:SS)	00:36:00	01:35:59
Run time per part (HH:MM:SS)	01:30:00	00:34:13
Total time per part (HH:MM:SS)	02:06:00	02:10:13
Per piece cost (including programming and fixturing with an assumed order of 50 pieces)	$198.86	$165.89

Table 4 - Comparison of the Company 2 vs. the iFAB Results

Quote line item description	Company 2 quote data	MAAT (iFAB) quote data
Material (4140 steel) – cost per piece	$25.00	$19.52
Setup		
Machine used	Haas VMC (CNC Mill)	
Machine setup - # setups		
Design / Engineering (programming) – Hrs. @ $75	4.0	
Programming and fixturing/tooling charges per piece	$6.00	
Setup time per part (HH:MM:SS)	00:07:30	1:39.40
Run time per part (HH:MM:SS)	00:55:00	00:49:00
Total time per part (HH:MM:SS)	01:02:30	02:28:40
Per piece cost (including programming and fixturing with an assumed order of 50 pieces)	$117.90	$186.13

The analysis shows that the costs of the same component from multiple SMEs can vary drastically. These variances may be due to many factors: differing hourly rates, equipment utilized to fabricate the parts, skill of the operator, etc. However, the one consistent item that RIT recognized was the difference between the SME and iFAB quotes for times. In general, the set-up time quoted by SMEs was shorter than that of iFAB, while the run times quoted by SMEs were longer than iFAB. This led to speculation that the time categories may be different in iFAB vs. the SME quotes, but RIT was unable to confirm exactly how iFAB quotes the times. It is possible that iFAB includes the load and unload times in the set-up time and the run time is simply machine time.

RIT intended to compare actual times collected by the SMEs during fabrication and compare those to the iFAB quotes. However, it was determined that the comparison would not be a good representation, as the SMEs stated they would fabricate the parts differently for a batch of 50 versus two pieces. This was a common thread among the manufacturers RIT met. In addition to the three SMEs that were contracted to fabricate parts, RIT met with three other SMEs who also stated the process would vary when ramping up to 50 parts. These three manufacturers chose to not provide quotes for this program.

6) RIT Analysis of the Orphan Parts Designs

In addition to the above analysis of iFAB, RIT performed a separate analysis of both iFAB and ANA utilizing the original marine yoke design, as well as the two modified designs presented by the SMEs. Based on design details, RIT hypothesized that the order of the marine yoke designs from least expensive to most expensive should be the Company 3 design due to the elimination of machining under the arms, the Company 1 and Company 2 design due the reduction in tool size to machine the radius under the arms, followed by the original design which requires a very small, 0.030”, radius under the arms.

Table 5 - Marine Yoke iFAB Comparison

Build Costs	Original Design	Company 1 & 2 Design	Company 3 Design
Total Manufacturing Cost	$163.52	$186.13	$165.89
Overhead Cost	$16.30	$20.86	$14.89
Materials Cost	$17.38	$19.52	$17.04
Labor Cost	$22.74	$28.49	$20.57
Setup Cost	$107.10	$117.25	$113.70
Build Schedule			
Total Mfg. Time	2H:08M	2H:28M:40S	2H:10M:13S
Run Time	38M:15S	49M	34M:13S
Setup Time	1H:30M:44S	1H:39M:40S	1H:35M:59S

The analysis of iFAB results in Table 5 does not follow the RIT hypothesis. RIT identified the following discrepancies:

1. Although all three components have the same external part envelope dimensions, the price of materials differs slightly across all designs.
2. Although the original design has the tight 0.030" radius under the arms, the total manufacturing cost and time was the lowest of the three options.
3. The Company 3 design should have the lowest set-up costs, but the original design was less.
4. The one area where Company 3 showed improvement in the results was in the run time and thus lower labor costs.

RIT is unable to explain the discrepancies in the above analysis, but the lower costs of the original design were consistent across multiple iterations of iFAB results.

Additionally, RIT expected the ANA results to show similar impacts on the Machinability Score index, with the index improving as you moved from the original design to the Company 1 & 2 design to the Company 3 design. The improvements to machinability can be seen in the outputs from ANA in Figure 6. The original machinability score was a 0.26, increasing to 0.46 when the radius is increased, and further increasing to 0.61 for the marine yoke without any machining under the arms (Company 3 design).

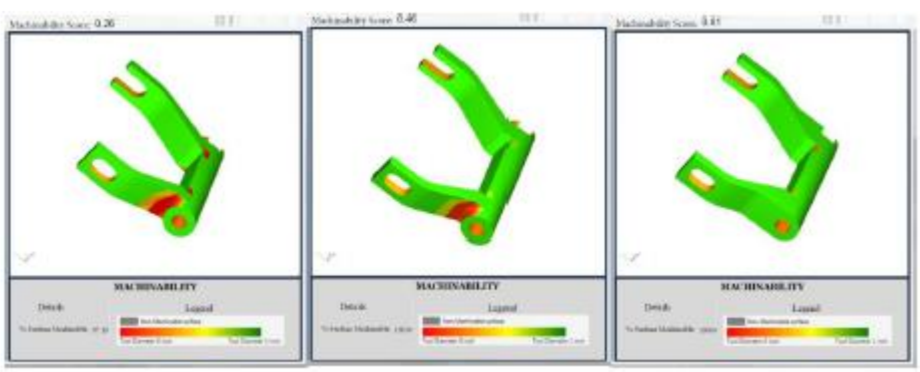


Figure 6 - Machinability Improvements seen in ANA

In addition, the overall manufacturability scores increased from 0.61 for the original to 0.66 for the Company 1 & 2 design, and finally 0.70 for the Company 3 design. The machining ANA outputs are

included with the delivery of this report in files titled “Machining ANA – Original.pdf”, “Machining ANA – Company 1 & 2.pdf”, and “MachiningANA – Company 3.pdf”.
RIT also ran the sand casting and die casting ANA tool on the marine yoke. The die casting ANA tool identified the arms as a concern when considering thick walled sections. Similarly, the bottom of the arms were identified as a concern for isolated heavy sections in the sand casting analysis.

The sand casting analysis also showed concerns over the feed distance of the Marine Yoke design. The concern is that the material may not completely feed into the highlighted areas, thus leaving voids in the final parts. For the die casting analysis, the die was identified as having thin walled sections in the pin through the bore area. Pin strength is directly impacted by core pin diameter.

7) iFAB Tool Feedback

One of the crucial outcomes of the project is understanding the SMEs overall feedback on the tool, how they would utilize the tool, and obtaining feedback for tool improvement. RIT performed a follow-up with each of the SMEs after providing training on iFAB and working with the SME to quote the component through iFAB. The feedback is summarized below.

- A general tolerance scheme is not optimal. The ability to specify tolerances to a feature is necessary. Otherwise, the iFAB quote will require identification of all features with non-general tolerances, and the additional cost to complete those features will need to be quoted outside the tool.
- The outputs of the iFAB tool don’t provide a clear understanding of how the hours and costs are assigned, i.e. set-up vs. manufacture vs. inspection. This makes comparison of the calculations against the rates difficult.
- Is programming included in the set-up costs?
- Is tooling/fixturing included in the set-up cost?
- What are the elements of run-time (e.g. how much time on roughing/finishing or on different features)?
- Customization of the tool to company specific machines and tools is highly desirable.
- The tooling and sequence of operations utilized for the iFAB quote, as well as unit process cost detail would be helpful in providing value added guidance on specific manufacturing cost drivers, as well as providing detail for the shop to actually lay out the manufacturing process that matches the quote.
- Customizing the labor, designer, and overhead rates to the shop, or more specifically to a job, would be helpful.
- Often times, manufacture may require an outside service to complete a job, e.g. coatings, but lead times do not exist in the Gantt chart for this. Allowing lead times to be added would be useful.
- Additional support beyond NX and Creo is necessary. Many companies are moving toward model-based design platforms like CATIA.
- Regardless of the modeling software used to create the data inputs for the aPriori product cost modeling software utilized by IFAB, the software needs to verify there were no translation errors for any parts generated by model-based software, e.g. CATIA. This is a common requirement for aerospace companies. Kubotek is an example of a software that verifies model translations. (Note: RIT understands this is a requirement for a specific SME. Use of iFAB does not preclude the SME from having to convert the models as they currently

do, but this was raised by the SME in question. The company was trying to limit the number of software packages required to complete the quoting process.).

- iFAB outputs are only useful if they are based on the specific machinery available in-house. Essentially, the SME needs to be able to have a quote that utilizes existing capabilities. An "ideal" quote that uses "best possible" equipment configuration would also be helpful for comparison – this would help a user understand his/her potential level of competitiveness.
- It would be helpful to link purchased parts to a supplier, e.g. McMaster-Carr, when applicable. Thus allowing consistently updated cost information.
- Inorganic coating list needs additional details to specify the coating type, e.g. nickel plating. The suggestion is that when nickel plating is selected, a sub-level of nickel plating types is shown for the user to pick from, e.g. electroless, watts non-bright, watts bright or sulfamate electroplating.
- A way to toggle between units (metric vs. standard) would be helpful as many machinists are accustomed to working in a specific unit.
- An SME questioned how stitch welds are specified. RIT explained that the weld is defined by the overall seam length in the costing software. The SME indicated that a common customer specification for stitch welds is to show the length of the stitch per unit of length, e.g. ¼" stitch per 1" seam length. The SME stated the customer specified stitch pattern can drive cycle time for the process.
- As the tool generates a quote, it would be helpful if this could be output into a usable format to generate routings, etc. Otherwise, the information would need to be generated again, negating the usefulness of the tool.
- Many of the GD&T callouts cannot be specified in the software, particularly a cylindricity callout, which was included in the Marine Yoke drawing.
- A U.S. manufacturing cost model is not sufficient. Costs differ drastically based on your location in the states, e.g. Alabama vs. NY.
- Heat treatment needs to be added as an option to material preparations.

A particular question was asked of each SME: How would you implement this in your business model? Feedback is summarized as follows:

- It would be desirable to have a less skilled person, possibly even an administrator, generate the quotes. A technical person could review the model and verify the system contained the appropriate equipment specs and capabilities, but then a non-technical person could enter the model and develop the quote.
- More examples of accurate quotes would need to be generated prior to acceptance of the tool.
- The software would need to integrate with the SME's ERP system. If not integrated, then at least allow for a digital hand-off, so the administrative staff doesn't have to manually input data from one system to the next.
- The system must allow quoting for multiple price points (volume price breaks), which is critical the SMEs business model.
- One SME proposed their ideal process flow as:
    1) Automate most of the quote response form generation.
    2) Process flow envisioned is that after the quoting software runs, the technical staff review the quote results and override any of the outputs that need to be revised. This again would require detail for unit operations.
    3) The administrative staff then takes the quote to respond to the customer.

Additionally, one of the SMEs provided a vision for their process flow and wish list for cost estimating software, see 11.

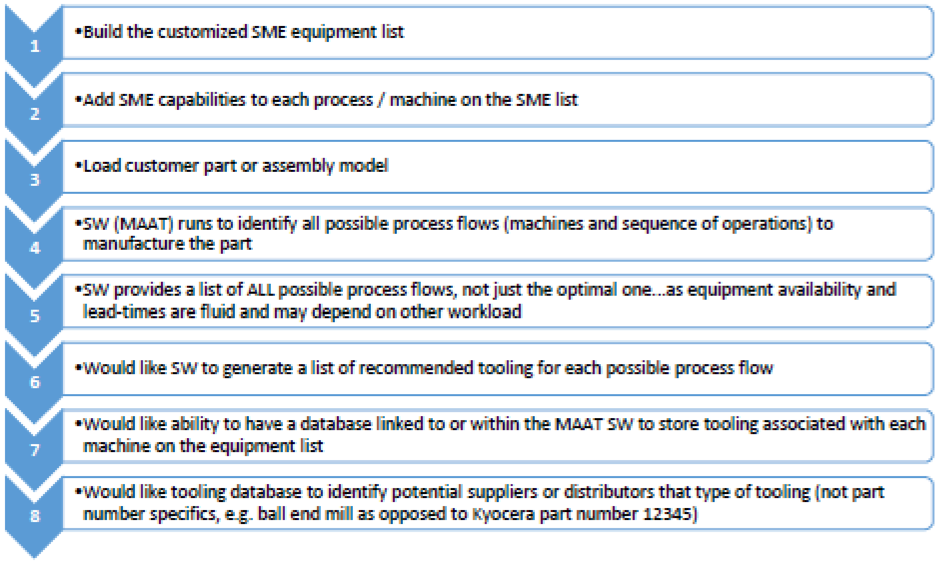


Figure 11 - Quoting Process Flow Vision

The general feedback was that the program was a step in the right direction, but that the availability to tailor the tool behavior by shop is critical to acceptance of the tool. Additionally, a tool of this type will require time to gain acceptance as companies will want to ensure that the quotes match their existing process before trusting the tool to perform the quotes.

With the ability to identify the equipment that could/should be utilized to produce a part, matchmaking purchasers with machine shops could be a fairly straightforward process. Allowing machine shops to "publish" their capabilities, e.g. machines, tooling, etc., should allow a tool to analyze the capable paths against shop capabilities. This would allow purchasers to easily identify shops that have the ability to make the part, thus strategically targeting calls for quotes, as opposed to publishing a blanket opportunity which may go unnoticed. All three of the SMEs thought this concept provided the largest value to their business.

8) Conclusions

The SMEs that RIT worked with on the orphan parts use case were very interested in the capabilities that the iFAB tool set could provide. Understanding that the tool is still a work in process, they provided valuable feedback with regard to necessary functionality before the tool could be adopted. The basic desired changes to iFAB functionality consists of:

- Customizable rate schedules for labor, engineering, etc.
- Company customizable machine and tool lists for analysis
- Addition of specific tolerances to component features
- Connectivity to an ERP system for creation of routings
- Selection of the desired quantities and number of lots being run

iFAB produced somewhat reasonable cost estimates when compared with the three SMEs, but the times produced by iFAB couldn't be directly compared to the times provided by the SMEs. The classification of hours by iFAB is not completely clear and effort should be made to make these outputs more transparent.

Additionally, all three of the SMEs were concerned about how much the iFAB tool may cost. The pricing structure for such a tool would have a significant impact on adoption. Many of the SMEs are working with lower cost software solutions and can't afford high recurring software costs. All three SMEs were interested in the DMDII/DMC model where a membership would provide access to the tool, with the understanding that the membership cost was not excessive.

With regard to the ANA, the tool performs well at highlighting areas of concern in manufacture. However, the SMEs engaged in the study were not as interested in the tool as all three of them typically act as fabrication shops and are provided customer designs to manufacture. In this model, they have highly skilled technicians who can identify the trouble spots easily through years of experience. However, the tool does have merit in an educational environment where students often spend significant time learning CAD and design skills, with less time spent understanding the impacts of a design on manufacturability. This tool could provide a useful, hands-on experience in combination with the typical CAD coursework. Similarly, a small company that does their own product design and may have inexperienced engineers on staff could benefit from the ANA tool.

Integration of the tools into the academic environment was one of the goals of the project. RIT worked with professors in both the College of Engineering (Mechanical Engineering) and the College of Applied Science and Technology (Manufacturing Engineering Technology, Mechanical Engineering Technology) to identify the best place to integrate the tools. The strongest linkage was within Manufacturing Engineering Technology program in a two-part course where students are required to design a product, cost the product, and design a production line for the product. The lead professor for those courses was extremely interested and was provided the training materials for review. However, it was shortly after this point that the decision was made to remove DMC integration from the project. This decision precluded utilization of the iFAB tool in the classroom. Unfortunately, iFAB was the tool that was of most interest to the professor; therefore, plans to integrate the tools into those courses ended. RIT still believes the ANA tool could be integrated into CAD courses, but was unable to achieve traction with any professors during the fall semester of 2017 to move the integration forward before the project ended.

VII. WESTERN ILLINOIS UNIVERSITY

WIU was responsible for providing machining feasibility feedback and should cost assessments on the bracket assembly using machining tools and software from their laboratory. Through the course of the project, WIU confirmed there is a steep learning curve to the CAM software required due to the complexity of the component being machined and the efforts to perform all machining on a lighter than normal 3-axis CNC mill. In producing the prototype part it was discovered that there were a number of geometric omissions in the supplied solid models. This may have occurred in the conversions of the solid models.

VII. APPENDICES

The project deliverables are listed below for reference:

- Automated Assembly Planning training and videos
- ANA training and videos
- Cost Analysis training and videos
- Creo installation training
- AutomatedAssemblyPlanner software
- DMDII Tech Showcase demo
- MAAT-and-cost-analysis-cloud
- NXMAATpluginstaller
- PMLALL
- Process model library user instructions
- scheduler
- wire-harness
- iFAB Tool Analysis
- iFAB Training
- Orphan Parts ANA Analysis
- Orphan Parts Drawings