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Additive Manufacturing and Digital Engineering Strategy Development

Principal Investigator: Dr. Daniel A. DeLaurentis
Co-Principal Investigator: Dr. Jitesh H. Panchal
Purdue University

**Sponsors: Dr. Vic S. Ramdass, SES, Deputy Assistant Secretary of Defense for Materiel
Readiness
Ms. Nickee L. Abbott, Director and Principal Advisor of Acquisition Intelligence
Division
Office of the Under Secretary of Defense for Acquisition and Sustainment**

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Research Team

Name	Org.	Labor Category
Daniel DeLaurentis	Purdue	Principal Investigator, Professor
Jitesh Panchal	Purdue	Co-Principal Investigator, Professor
Nate Hartman	Purdue	Professor
Ananth Iyer	Purdue	Professor
Steven Dunlop	Purdue	Managing Director
Dutt Thakkar	Purdue	Associate Project Manager
Ashritha Setlur	Purdue	Data Analyst
Qian (Alex) Shi	Purdue	Graduate Research Assistant
Dalia Bekdache	Purdue	Graduate Research Assistant
Clint Hanthorn	Purdue	Software Engineer
Ian Walter	Purdue	Graduate Research Assistant
Atharva Sonanis	Purdue	Graduate Research Assistant
Waterloo Tsutsui	Purdue	Senior Research Associate
Christopher Williams	Virginia Tech	Professor
Amanda Wei	Virginia Tech	Graduate Research Assistant
Lindsey Bezek	Virginia Tech	Post-Doctoral Associate

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Executive Summary

Additive manufacturing provides an alternative approach for manufacturing products across the supply chain. Some of the benefits of using additive manufacturing are inventory reduction in the supply chain yet increasing supply chain resilience through alternate options, quicker response to surge demands and warfighter readiness, and manufacturing products with complex design while actively reducing the number of serviceable components.

The following aspects of the research activity (i.e., Decision Support Tool, Use Cases 1-3, and Digital Engineering Strategy) are distinguishing features accomplished in the research in support of the sponsor's needs.

Decision Support Tool for Additive Manufacturing: We developed a “Decision Engine,” which forms the basis of an additive manufacturing decision-support tool. The Decision Engine provides the users with an algorithmic view of the variables to make an optimized decision regarding where and how additive manufacturing can have the most impact. More specifically, in the Decision Engine that we developed, each decision by a decision maker can be split into the objectives of the decision maker and the alternatives. Each alternative comprises the relevant attributes to the decision problem. As a part of the user interface, the final output from the Decision Engine is a visualization allowing the decision-maker to see the relative performance of each alternative considered. The tool is intended to assist the decision-maker by providing them with quantitative information about the usefulness of each alternative relative to others. The process of using the Decision Engine is described in the context of decisions being made in an organizational hierarchy, where 1) one individual makes the final decision and 2) a team of engineers determines the information relevant to the decision context. Once the decision maker has established the decision context, the technical engineers may begin translating this information into data usable by the engine. Finally, the decision support tool described herein is demonstrated using three use cases.

Use Case 1: Aircraft Fleet Maintenance using Additive Manufacturing: Use Case 1 identified a unique relationship among three variables: the cost of utilizing additive manufacturing, the penalty incurred due to mission delay, and the utilization of additive manufacturing. If the cost of utilizing additive manufacturing per unit is constant, this results in 1) the increased cost of penalty due to mission delay and 2) the increased utilization of additive manufacturing. On the other hand, if the cost of the penalty is constant, this results in 1) the increased cost of utilizing additive manufacturing for aircraft maintenance and 2) the decreased utilization of additive manufacturing.

Use Case 2: Spacecraft Applications: Use Case 2 demonstrated how the Decision Engine could be integrated into the mission engineering process of designing and manufacturing satellite components – specifically to identify the optimal machine-material pair for an additive manufactured component. Decision-makers often also need to tackle “manufacturability” considerations at a portfolio level. Based on our research, we identified the possibility of

enhancing the Decision Engine to support additive manufacturing use decisions pertaining to a portfolio of parts (e.g., which combinations of additive manufacturing options best support the production of a variety of satellite or spacecraft parts). In addition, as portfolio selection problems are likely to involve more stakeholders, the Decision Engine interface can also be expanded to be customizable for different decision-makers (e.g., project manager vs. component engineer) to support hierarchical decision-making within an organization.

Use Case 3: Design, Manufacturing, and Maintenance of Aircraft Components: Use Case 3 applied the Decision Engine to compare the utility of several manufacturing approaches for producing small-batch custom aircraft components. More specifically, we looked at scenarios where an aircraft manufacturing company is looking for aircraft replacement components (i.e., aileron bellcranks) using both additive and traditional manufacturing. We analyzed the use case by incorporating the two scenarios, where the objective of the first scenario was to explore the replication of the original component design and material across different manufacturing processes (i.e., original design, original material, and various manufacturing processes). In contrast, the objective of the second scenario was to explore topology optimized design compared to the original design and material across different manufacturing processes (i.e., new design, original material, and various manufacturing processes). In addition, as we improve the Decision Engine, we are looking at the possibility of changing both the design and material of the aircraft components in the future.

Digital Engineering Strategy: The Digital Engineering Strategy section of this report aimed to review the recommendations and requirements proposed by the DoD for metal additive manufacturing adoption and to develop guidance for AIRC 's use case. This review originated a sample roadmap and a suggested data package framework for metal additive manufacturing methods and tools, which supports the AIRC in developing data packages necessary to support the adoption and continued use of metal additive manufacturing techniques within the DoD acquisition functions. These recommendations have been developed based on the review of standards, literature, and DoD recommendations. The results of this report can (and should) be validated and refined by conducting case studies of AM implementation through the suggested roadmap and data packages.

Introduction

The overall objective of this task was to develop tools and knowledge to support the development of an additive manufacturing supply chain sustainment strategy and a digital engineering strategy. As we initiated the research effort at the beginning, we asked ourselves: Can the whole supply chain and sustainment strategy change given the additive manufacturing opportunities instead of traditional manufacturing? In what timeframe? What are the limits (e.g., materials science; systems engineering; cost; reliability; infrastructure)? To effectively perform mission engineering and ensure readiness for additive manufacturing, we set up a digital environment ready for sustainment and have the capabilities we need when we need them.

This subtask, WRT-1049.4, focused on the data and framework surrounding the opportunity to exploit additive manufacturing. More specifically, we explored the following areas:

- Identification of necessary data in digital system models to understand how Additive Manufacturing could support system readiness and sustainment;
- Isolation of the most critical system elements from the perspective of sustainment; identification of the variables that are key to understanding criticality from this point of view;
- Development of a framework that would allow the focused allocation of additive manufacturing to impact system readiness and sustainment; and
- Development of a framework of items and contractual elements that would be critical for the DoD to negotiate during the contract phase (e.g., any intellectual property rights or options needed to support an Additive Manufacturing strategy for certain types of supplies and equipment).

Accordingly, we explored additive manufacturing as a systems engineering problem as follows: First, we identified the critical decision and analysis variables and created a framework to understand how these variables impact each other. Second, we transferred the above framework into an algorithmic view of these variables to make an optimized decision regarding where and how additive manufacturing can have the most impact. Third, we developed an interactive decision support tool (i.e., “Decision Engine”) in additive manufacturing, supply chain, and digital engineering as part of the overarching goal in mission engineering.

This report starts with a description and conceptual background on the decision support tool. Then, we discuss three use cases we analyzed to create the decision support tool: 1) Aircraft Fleet Maintenance using Additive Management, 2) Spacecraft Applications, and 3) Design, Manufacturing, and Maintenance of Aircraft Components. Finally, the report concludes with the presentation of a roadmap for creating digital technical data packages to adopt additive manufacturing.

Decision Support Tool for Additive Manufacturing

1.1 OVERALL SCENARIO

Additive Manufacturing (AM) is playing an increasingly important role in DoD acquisition and sustainment. Decisions about additive manufacturing technology are made within various agencies ranging from USD(A&S) to individual military departments. Decision makers range from high-level decision makers interested in overall mission effectiveness to field engineers who are responsible for operating specific equipment. There is a wide range of decisions related to additive manufacturing, such as decisions about whether to use additive manufacturing or traditional manufacturing, supplier selection, a decision on contract type; AM technology selection, machine and material selection, and process parameter selection (e.g., layer thickness, speed, part orientation). The decision-making criteria also vary widely from high-level attributes such as resilience and mission effectiveness to technical attributes such as part accuracy and

structural performance. Other decision factors may include material availability, machine availability, machine maintainability, competition, technology capability, technology maturity, cost, number of parts, intellectual property ownership, and supply chain resilience.

While there are several initiatives to support specific types of decisions within the AM domain, there is a lack of a decision support tool that can be adopted or customized to support different decision makers for a range of AM-related decisions. In this task, we address this limitation by developing the Decision Engine and demonstrating it for three use cases relevant to mission engineering. The activities carried out in this project are illustrated in Figure 1.

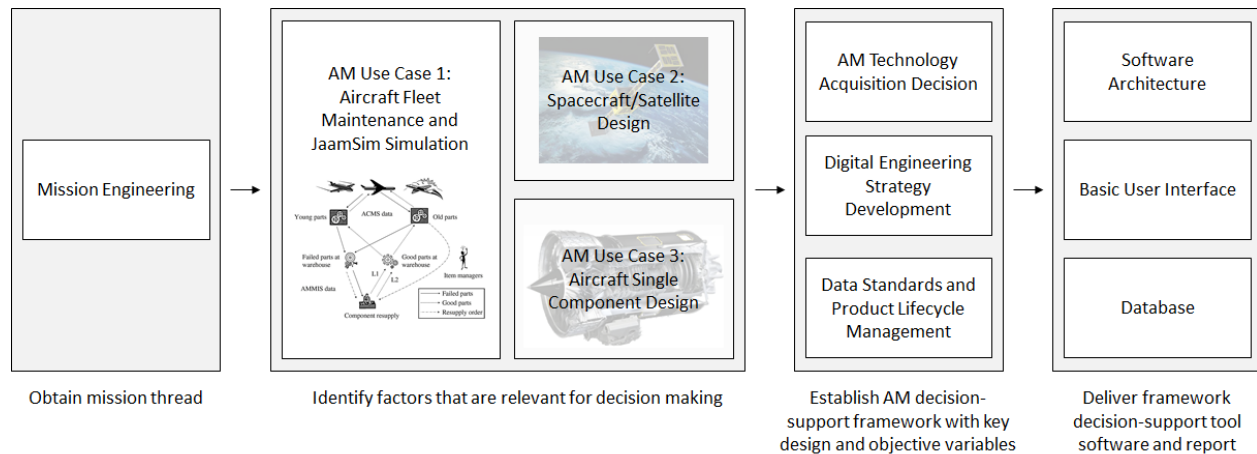


Figure 1 Overall development process

1.2 VISUALIZATION OF DECISION ENGINE

Each decision to be made by a decision maker can be split into two types of components: the objectives of the decision maker (e.g., what their goals are, what they want to improve, minimize, and prevent from happening) and the alternatives (the different options the decision maker can choose from). Each alternative is composed of the relevant attributes to the decision problem, examples of which can be seen in the three use cases. The final output from the Decision Engine is a bar chart displaying the expected utility values of each alternative considered and is intended to assist the decision maker by providing them with quantitative information about the usefulness of each alternative relative to others.

For this project, we make several assumptions that impact the implementation of the Decision Engine. One assumption is that each decision has a finite number of alternatives. This assumption implies that the Decision Engine tool would not be suitable for choosing the optimal parameters in a continuous design space. However, if the options could be constrained to a finite subset of parameters, then this tool could be used. Another assumption is that the attributes of any alternative are utility-independent. If two attributes were not utility independent, then as the value of one attribute changes, the utility that the decision maker gets from another attribute will change. The assumption of utility independence is standard in the literature (Fernández et

al.) and greatly reduces the complexity of implementation and makes the process of using the engine significantly easier for an end-user.

The process of using the Decision Engine is described in the context of decisions being made in a hierarchy, with one individual making the final decision and an individual or team of technical engineers who determine the information relevant to the decision context. The general steps for the decision-making process are outlined in (Fernández et al.). In the context of a hierarchy, we assume that the decision makers and technical engineers are distinct groups, but they could, in practice, be the same. The decision maker should set out the specifics of the decision, answering questions such as:

- What exactly is the decision being made?
- What are the specific objectives or goals that want to be achieved from this decision?
- What kind of attributes will be important when comparing multiple alternatives?

Once the decision context has been clearly established by the decision maker, the technical engineers may begin translating this information into data usable by the engine. The information about the decision scenario is fed into the Decision Engine via .json files, which are a type of structured data file that is human-readable. There are two categories of files used by the Decision Engine: The decision objective file and the alternative information files.

Decision Objective File

The first type of file is the decision objective file, and there is typically only one of these in each decision-making context. The decision objective file contains information specific to the decision context and the decision maker. In this file, each attribute being considered by the final decision maker has some general information listed, such as its name, description, and units of measurement, as well as information relating to the utility function of the decision maker. This information describes the general shape of the utility function, such as the risk attitude of the decision maker and whether it is monotonically increasing, decreasing, or neither. Lastly, specific numerical data about each utility function is provided. Each utility function takes the form of the equation $u_i(x) = a + bx + ce^{dx}$, where i is the index of the attribute being considered, x is the attribute's value, $u_i(x)$ is the utility of attribute i with value x , and a , b , c , and d are the specific parameters of the utility function. The decision objective file contains these parameters a , b , c , and d . The information about the decision context must be collected from the final decision maker or someone else with a clear understanding of the goal of the decision.

Alternative Information Files

The other files used by the Decision Engine contain information about the alternatives being considered. Each file contains information about the attributes relevant to the specific decision being made. For the alternative attribute information, the data can either be collected manually by technical engineers or automatically if there is access to a relevant database. Currently, each attribute is given either as a constant value or as a uniform distribution if there is uncertainty about the attribute's value. We plan to implement additional distributions in the future to enable

a more accurate representation of the uncertainty in various attributes. Figure 2 shows the way information flows into the two types of files and then into the Decision Engine.

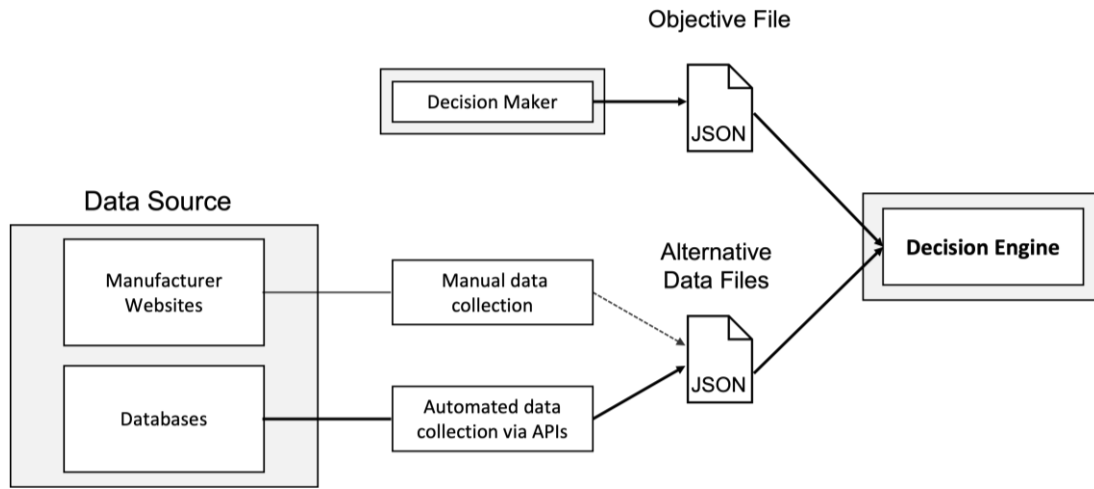


Figure 2 Decision Engine information flow

User Interface

Figure 3 depicts the main screen of the Decision Engine's user interface, which allows the selection of use cases for analysis. These use cases come from folders containing JSON data files, so these can be added to, removed from, or updated as needed. After the user selects a use case (i.e., Use Case 1, 2, or 3) on the main screen (Figure 3), another user interface appears (Figure 4). This user interface (Figure 4) displays a description of the decision being made at the top of the screen, followed by two tables underneath: Alternatives and Attributes tables.

The first table, Alternatives, lists the alternatives and their utility scores. The highest utility score is highlighted in bold italic font. If the mouse pointer hovers over an alternative, its information is shown (Figure 5) in a tooltip. In the figure shown (Figure 5), detailed information about the first alternative appeared since the user hovered over the first alternative in the Alternatives table.

The second table, Attributes, lists the attributes with their lower, ideal, and upper values, units, and weights which are adjustable using sliders. Further information about each attribute can be seen in a tooltip when the mouse pointer hovers over the attribute name (Figure 6). In the figure shown, the detailed information about cost appeared since the user hovered over the "cost" in the Attribute table.

The last item in the user interface is the results plot in the form of a colored bar chart (Figure 4). The expected utility scores are shown for each alternative and are updated automatically as the weight sliders are adjusted in the Attributes table. For instance, the bar chart in Figure 4 shows that Alt 4 has the highest utility score. The user can also confirm this result using the bold font in the table above, where the fourth alternative has the highest utility score.



Figure 3 Main screen for “Decision Engine for Additive Manufacturing”

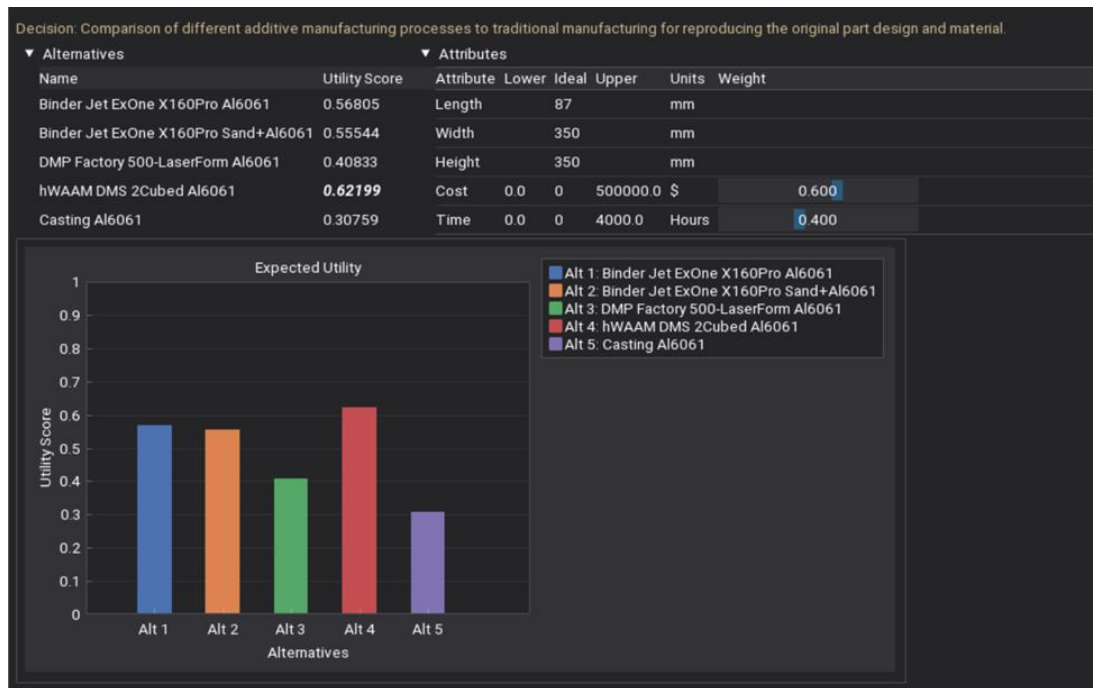


Figure 4 Example of the user interface after the user selects the use case

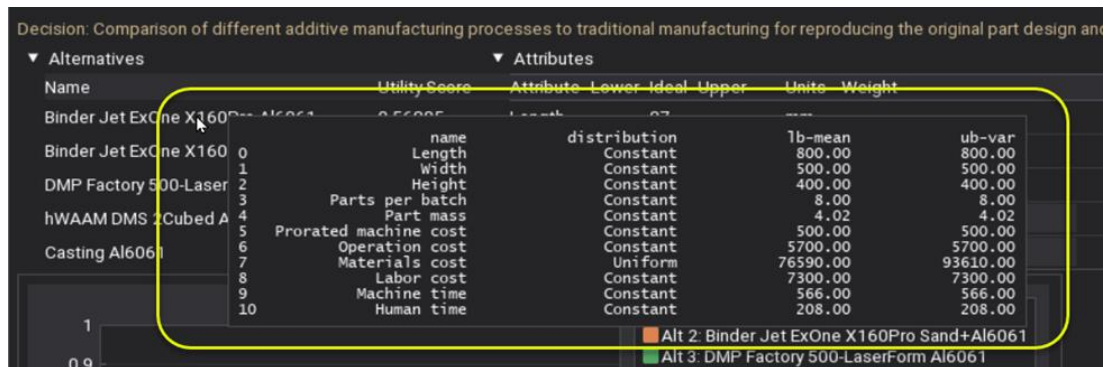


Figure 5 Detailed information on one of the alternatives in the “Alternatives” table

Attributes					
Attribute	Lower	Ideal	Upper	Units	Weight
Length		87		mm	
Width		350		mm	
Height		350		mm	
Cost					0.600
Total cost to print 1000 parts					
Time					0.400

Alt 1: Binder Jet ExOne X160Pro Al6061
Alt 2: Binder Jet ExOne X160Pro Sand+Al6061
Alt 3: DMP Factory 500-LaserForm Al6061
Alt 4: hWAAM DMS 2Cubed Al6061

Figure 6 Detailed information on one of the attributes in the “Attributes” table

Use Case 1: Aircraft Fleet Maintenance using Additive Manufacturing

1.3 BACKGROUND/OVERVIEW

The objective of Use Case 1: Aircraft fleet maintenance using additive manufacturing is to minimize the sum of mission delay costs and additive manufacturing marginal cost for aircraft. The decision variable is to choose the threshold at which additive manufacturing is used to optimize this cost. Mission delay cost refers to delays from the mission schedule start.

In the next sections, we elaborate upon the simulation software – JaamSim, used for building a simulation model and the analysis. It also discusses the inputs and assumptions made to build the simulation model. In addition, we also go through the data that is collected through the simulation model along with the calculations performed using this data to derive our conclusions. These calculations have also been represented visually using line graphs to identify the optimal threshold value.

The schematic diagram shown in Figure 7 represents the foundation for building the simulation model for use case 1 of the project. We start with an aircraft as a resource that is assigned to perform a mission for the U.S. Coast Guard. Each aircraft completes the mission after it is checked for mission readiness (in this case, we define mission readiness for an aircraft as having no parts that may fail during service). Post completion of the mission, the aircraft undergoes inspection again to check for failures that arise due to wear out (i.e., unscheduled maintenance), or the part may be flagged for regular maintenance (i.e., scheduled maintenance).

Upon failure, we assume that the part must be replaced and cannot be repaired for further use. The aircraft parts to be replaced can be produced using traditional manufacturing or additive manufacturing. This decision is based on the aircraft inventory threshold. Once the number of aircraft in the inventory drops below the threshold, we switch to additive manufacturing to complete maintenance requests in a shorter time frame, avoiding mission delay or penalty (given that traditional manufacturing has a longer lead time).

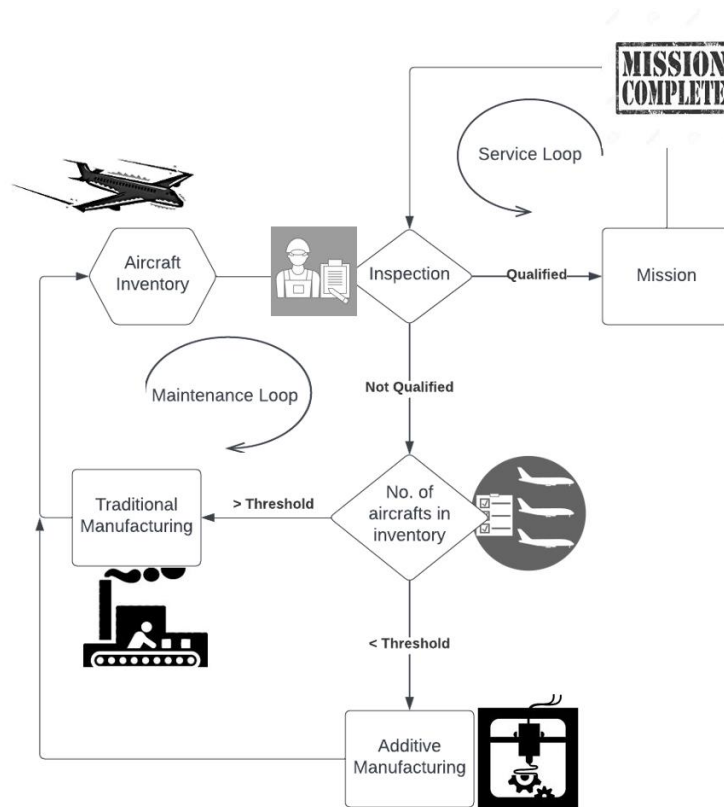


Figure 7 Schematic diagram depicting the concept implemented in the simulation model

1.4 SIMULATION MODEL

Simulation Software

An open-source software, Java Animation Modelling and Simulation, abbreviated as JaamSim, was used to design the simulation model. JaamSim offers an interactive graphical user interface, 3D modeling, and customization of simulation runs. A basic layout of the software is shown in Figure 8.

The software is highly flexible in redefining the built-in elements to suit users' requirements and further make changes. For this project, built-in objects used to build the model include,

- Entities to represent requests and resource pools to represent the inventory containing the cluster of aircraft
- Objects for process flow where various priorities and resource allocation will be defined (queues, seize, release, and assign)
- Text objects for labeling and documentation
- Probability distributions for sampling and Generators to periodically generate service requests
- Graphical objects to represent the missions coming into the queue and the aircraft.

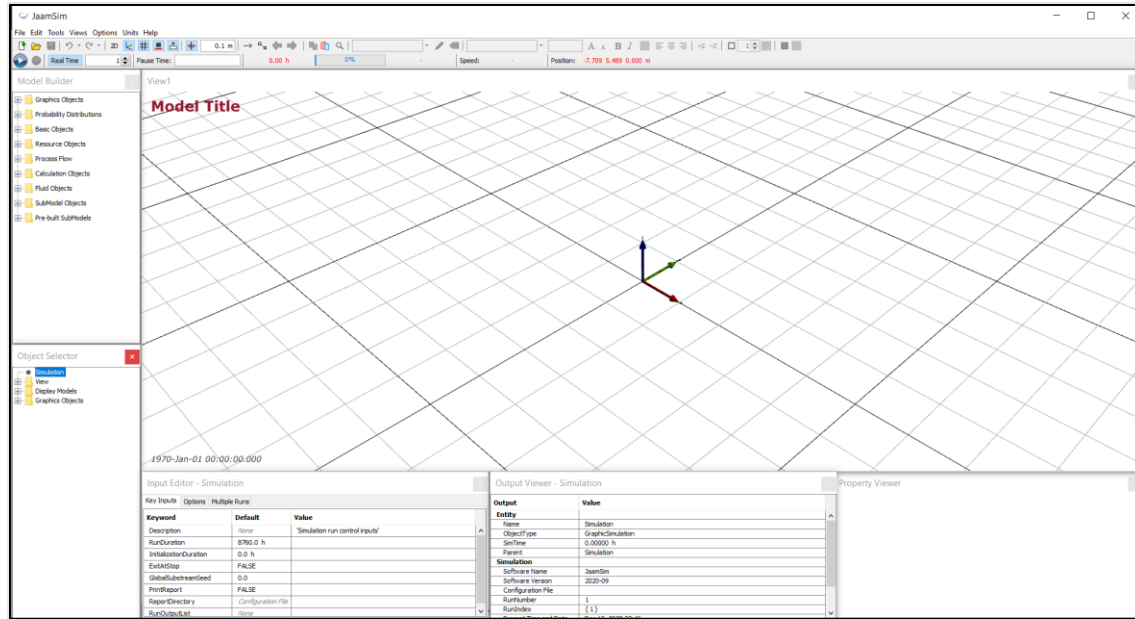


Figure 8 Simulation software JaamSim layout

Model Setup, Inputs, and Assumptions

For the sample runs, the simulation model is set up with initial parameters that allow us to structure the data collection process and support our analysis. Randomization was incorporated into the simulation by assigning distributions to the simulation entities (e.g., mission generation and mission duration time). The distribution seeds were fixed, and the distributions were defined to standardize the data collection across multiple runs. The number of aircraft in the inventory was set to 10 to account for scalability within the simulation model.

Before each simulation run, we fix the inventory threshold, i.e., the number of aircraft in the inventory that are mission ready, indicating a shortage of resources. At this inventory threshold, we switch from using traditional manufacturing to additive manufacturing (e.g., an inventory threshold set at four would imply that each time the number of aircraft in the inventory fall below 4, we process maintenance requests through additive manufacturing). The aircraft in the inventory is assumed to be mission ready, and they are initialized as new resources, having operated for 0 flight hours.

The simulation starts with missions being generated, and the inter-arrival time between successive missions is defined by a uniform distribution with a minimum value of 4 hours and a maximum value of 24 hours over a total simulation time of 8760 hours (365 days). Each mission is assumed to require exactly one aircraft to complete the service and is assigned an aircraft from the inventory by the resource seize entity. Each mission has a definite duration for completion, which is assigned to the mission by a normal distribution with a mean of 38 flight hours, a standard deviation of 7.8 flight hours, and is truncated at 0 flight hours. Each mission is also assigned a priority of high with a probability of 0.2 and a priority of low with a probability of 0.8.

As a mission is completed, the aircraft that was assigned as a resource must undergo inspection. This can either lead to scheduled maintenance or unscheduled maintenance. Each aircraft undergoes scheduled maintenance after 500 flight hours of operation and unscheduled maintenance with 0.99 probability. Given that our objective is to minimize mission delays due to maintenance activities that result in a lack of resources, the probability for maintenance is set high to ensure that each aircraft undergoes some maintenance. In such a scenario, the number of aircraft in the inventory falls below the threshold set regularly, allowing us to determine the critical threshold value if the maintenance process is to be performed frequently.

The time to complete maintenance through the traditional manufacturing method is defined by a normal distribution truncated at 0 flight hours, with a mean of 100 flight hours and a standard deviation of 20 flight hours. In comparison, the time to complete maintenance using additive manufacturing is set at 53% less than traditional manufacturing, which captures the time benefit of completing maintenance using additive manufacturing in a time-sensitive situation. Therefore, additive manufacturing is defined by a normal distribution truncated 0 flight hours with a mean of 47 flight hours and a standard deviation of 10 flight hours.

Each simulation setup is duplicated for different parts of an aircraft. The information for the parts was taken from the paper *“Efficient Supply Chain Management at the U.S. Coast Guard Using Part-Age Dependent Supply Replenishment Policies.”* (Deshpande et al.). The distributions are adjusted in accordance with the deterioration the specific part undergoes upon frequent usage. The simulation model for one part is shown in Figure 9.

Aircraft Fleet Maintenance Using Additive Manufacturing

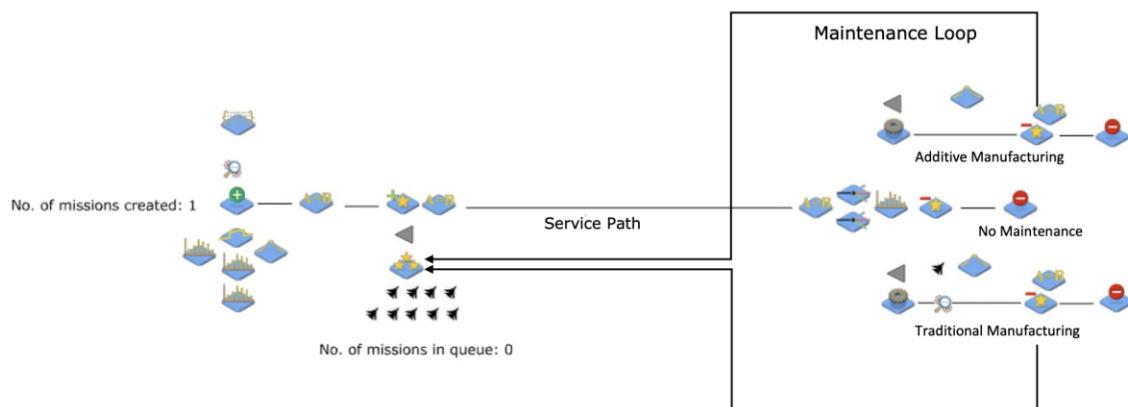


Figure 9 Simulation model for wheels in an aircraft

Data Collection

As the simulation runs, missions are generated regularly but cannot be processed due to a lack of aircraft in the inventory. The aircraft may either be already completing a mission or undergoing maintenance. Due to this constraint, the missions form a queue ordered first by priority and then by order of first come, first serve. This queue is essential to capture the delays that occur due to a lack of resources caused by our maintenance activities.

Post each simulation run, we capture the following values for a given inventory threshold:

- The average queue time the missions had to wait in the queue because of the unavailability of aircraft in the inventory to be assigned to the mission
- The total number of missions generated across the total simulation time
- The total number of maintenance requests that were completed using the additive manufacturing process
- The total number of maintenance requests that were completed using the traditional manufacturing process

Each of the values above is captured by varying the inventory threshold between 1 and 10 (maximum of 10 aircraft in the inventory). The range of the inventory threshold accounts for both scenarios where only traditional manufacturing is used and a scenario where only additive manufacturing is used for maintenance activities.

The values are tabulated as shown in Table 1. Transformations and calculations are performed on this data, as elucidated in the next section.

Table 1 Tabulation of data collected for the maintenance of wheels in the aircraft

Inventory Threshold	No. of maintenance requests (Traditional Manufacturing)	No. of maintenance requests (Additive Manufacturing)	Average queue time (Cumulative across missions) (hours)	Total no. of missions generated
1	407	206	2.788	622
2	352	261	1.589	622
3	260	353	0.578	622
4	188	425	0.261	622
5	115	498	0.166	622
6	37	576	0.000	622
7	2	611	0.000	622
8	1	612	0.000	622
9	0	613	0.000	622
10	0	613	0.000	622

1.5 DATA ANALYSIS AND VISUALIZATION

To perform our analysis, we calculated the total costs incurred as a summation of the total penalty due to mission delay and the total marginal cost of using additive manufacturing for maintenance (over and above traditional manufacturing), as shown in the equation below.

The total marginal cost of using additive manufacturing is calculated as the product of the number of aircraft maintenance requests processed and the cost of processing a part through additive manufacturing.

The total penalty is calculated as the product of the cumulative average time a mission was in the queue, the total number of missions generated, and the cost of mission delay per mission per hour.

$$\text{Total Cost} = \text{Marginal Cost of AM} + \text{Penalty Cost}$$

Where

$$\text{Marginal Cost of AM} = \text{Maintenance Requests Completed by AM} * \text{Cost of Using AM (per Unit)}$$

$$\text{Penalty Cost} = \text{Cumm. Avg. Queue Time} * \text{No. of Missions Generated} * \text{Cost of Delay (per Unit per Hour)}$$

Table 2 shows the calculated cost based on the incremental total cost of the penalty. Then, the calculation is plotted in Figure 10 with the inventory threshold on the x-axis and the total cost (total cost of penalty + total cost of using additive manufacturing) on the y-axis for each marginal cost of additive manufacturing (per unit), and the cost of penalty due to mission delay (per mission per hour).

The calculations are duplicated by incrementing the cost of processing maintenance requests through additive manufacturing (per unit) and fixing the cost of penalty due to mission delay (per mission per hour) to get the following values (Table 3). Then, the calculation is plotted in Figure 11.

Table 2 Calculation with an incremental total cost of the penalty

Marginal cost of using additive manufacturing (per unit)	\$5,000	\$5,000	\$5,000	\$5,000	\$5,000
Incremental cost of penalty due to mission delay (per hour per mission)	\$1,000	\$2,000	\$3,000	\$4,000	\$5,000
Inventory Threshold					
1	\$2,764,276.41	\$4,498,552.82	\$6,232,829.23	\$7,967,105.64	\$9,701,382.05
2	\$2,293,111.64	\$3,281,223.27	\$4,269,334.91	\$5,257,446.55	\$6,245,558.18
3	\$2,124,439.90	\$2,483,879.80	\$2,843,319.70	\$3,202,759.60	\$3,562,199.50
4	\$2,287,241.24	\$2,449,482.47	\$2,611,723.71	\$2,773,964.94	\$2,936,206.18
5	\$2,593,279.01	\$2,696,558.02	\$2,799,837.03	\$2,903,116.04	\$3,006,395.05
6	\$2,880,000.00	\$2,880,000.00	\$2,880,000.00	\$2,880,000.00	\$2,880,000.00
7	\$3,055,000.00	\$3,055,000.00	\$3,055,000.00	\$3,055,000.00	\$3,055,000.00
8	\$3,060,000.00	\$3,060,000.00	\$3,060,000.00	\$3,060,000.00	\$3,060,000.00
9	\$3,065,000.00	\$3,065,000.00	\$3,065,000.00	\$3,065,000.00	\$3,065,000.00
10	\$3,065,000.00	\$3,065,000.00	\$3,065,000.00	\$3,065,000.00	\$3,065,000.00
Minimum total cost for penalty cost/AM cost pair	\$2,124,439.90	\$2,449,482.47	\$2,611,723.71	\$2,773,964.94	\$2,880,000.00
Threshold with minimum total cost	3	4	4	4	6

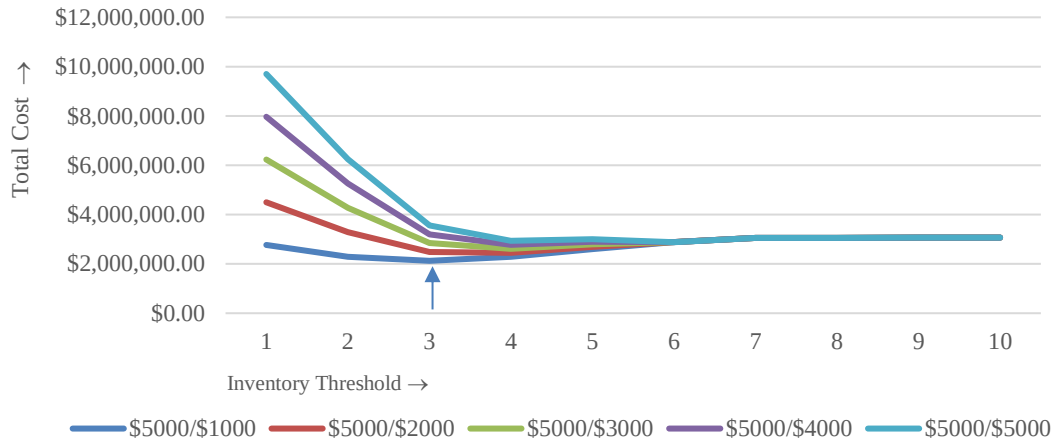


**Figure 10 Total cost vs. inventory threshold based on mission delay
(Incremental penalty cost due to mission delay)**

Table 3 Calculation with an incremental total cost of additive manufacturing

Incremental Marginal cost of using additive manufacturing (per unit)	\$500	\$1,000	\$1,500	\$2,000	\$2,500
Cost of penalty due to mission delay (per hour per mission)	\$1,000	\$1,000	\$1,000	\$1,000	\$1,000
Inventory Threshold					
1	\$1,837,276.41	\$1,940,276.41	\$2,043,276.41	\$2,146,276.41	\$2,249,276.41
2	\$1,118,611.64	\$1,249,111.64	\$1,379,611.64	\$1,510,111.64	\$1,640,611.64
3	\$535,939.90	\$712,439.90	\$888,939.90	\$1,065,439.90	\$1,241,939.90
4	\$374,741.24	\$587,241.24	\$799,741.24	\$1,012,241.24	\$1,224,741.24
5	\$352,279.01	\$601,279.01	\$850,279.01	\$1,099,279.01	\$1,348,279.01
6	\$288,000.00	\$576,000.00	\$864,000.00	\$1,152,000.00	\$1,440,000.00
7	\$305,500.00	\$611,000.00	\$916,500.00	\$1,222,000.00	\$1,527,500.00
8	\$306,000.00	\$612,000.00	\$918,000.00	\$1,224,000.00	\$1,530,000.00
9	\$306,500.00	\$613,000.00	\$919,500.00	\$1,226,000.00	\$1,532,500.00
10	\$306,500.00	\$613,000.00	\$919,500.00	\$1,226,000.00	\$1,532,500.00
Minimum total cost for penalty cost/AM cost pair	\$288,000.00	\$576,000.00	\$799,741.24	\$1,012,241.24	\$1,224,741.24
Threshold with minimum total cost	6	6	4	4	4

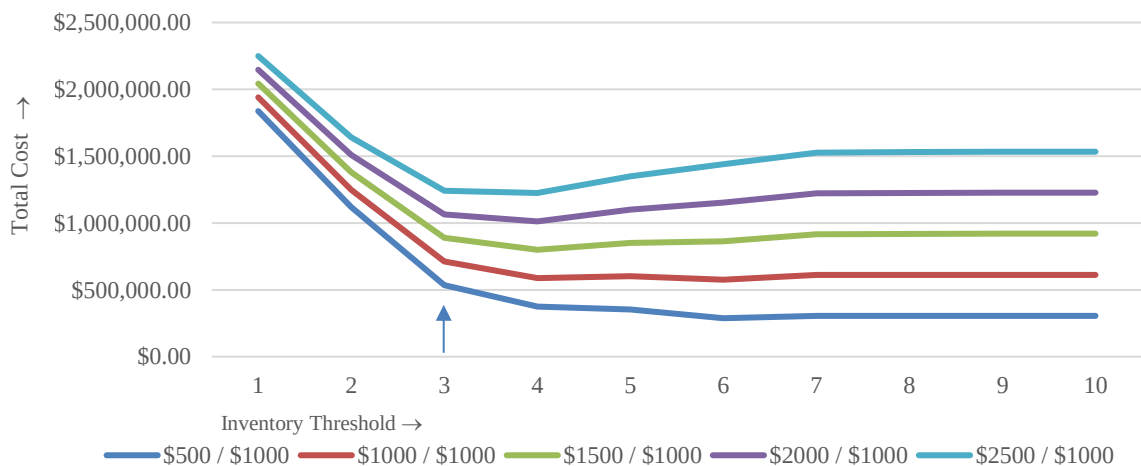


**Figure 11 Total cost vs. inventory threshold based on the use of AM
(Incremental margin cost due to the use of AM)**

1.6 SUMMARY/FUTURE WORK

Given the cost of utilizing additive manufacturing for maintenance (per unit) and the cost of penalty (per mission per hour), we evaluated the AM utilization:

- Keeping the AM cost constant at \$5,000 and increasing the penalty cost, we observe that the optimal threshold at which we switch to AM has an increasing trend
- As the penalty cost increases, we see the optimal threshold moving to the right, suggesting that we utilize AM more often when the penalty cost is high
- Keeping the cost of penalty due to delay constant at \$1,000 and increasing the cost of AM, we see a decreasing trend in the optimal threshold value
- As the premium paid for using AM increases, we see that the optimal threshold moves to the left. This observation suggests that when the cost of penalty for mission delay is constant, the cost of AM usage increases. As a result, we utilize the AM much less frequently

In conclusion, through our analysis, we were able to identify a unique relationship between the cost of utilizing additive manufacturing, the penalty incurred due to mission delay, and the utilization of additive manufacturing. If the cost of utilizing additive manufacturing per unit is constant, the higher the cost of penalty due to mission delay, the utilization of additive manufacturing increases. Given the cost of the penalty is constant, the higher the cost of utilizing additive manufacturing for aircraft maintenance, the lower the additive manufacturing utilization.

Use Case 2: Spacecraft Applications

1.7 BACKGROUND/OVERVIEW

AM has been gaining traction in space engineering applications owing to its ability to produce lightweight parts, improve build-to-fly ratios, and be cost-effective at low build volumes. However, decisions on AM use involve multiple attributes and stakeholders and have wide-ranging implications on supply chain operations. A utility-based Decision Engine is well-placed to support prospective users in evaluating AM-use options. For this use case, we focused on decision attributes relating to the performance, cost, and time of incorporating AM in the design and manufacturing of satellite parts. The four-step problem abstraction process is summarized in Figure 12 and elaborated below.

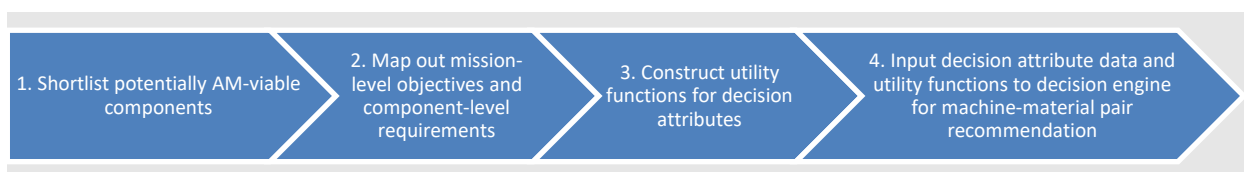


Figure 12 Problem abstraction process

1.8 SHORTLIST AM-VIABLE COMPONENTS

The first step is to shortlist components that are more likely to be viable for AM adoption. Satellite systems generally comprise three major subsystems: (1) the bus platform that provides structural and operational support for the overall satellite system, (2) the payload to execute the overall mission objective, and (3) ground support systems to control and coordinate the satellite operations (Figure 13).

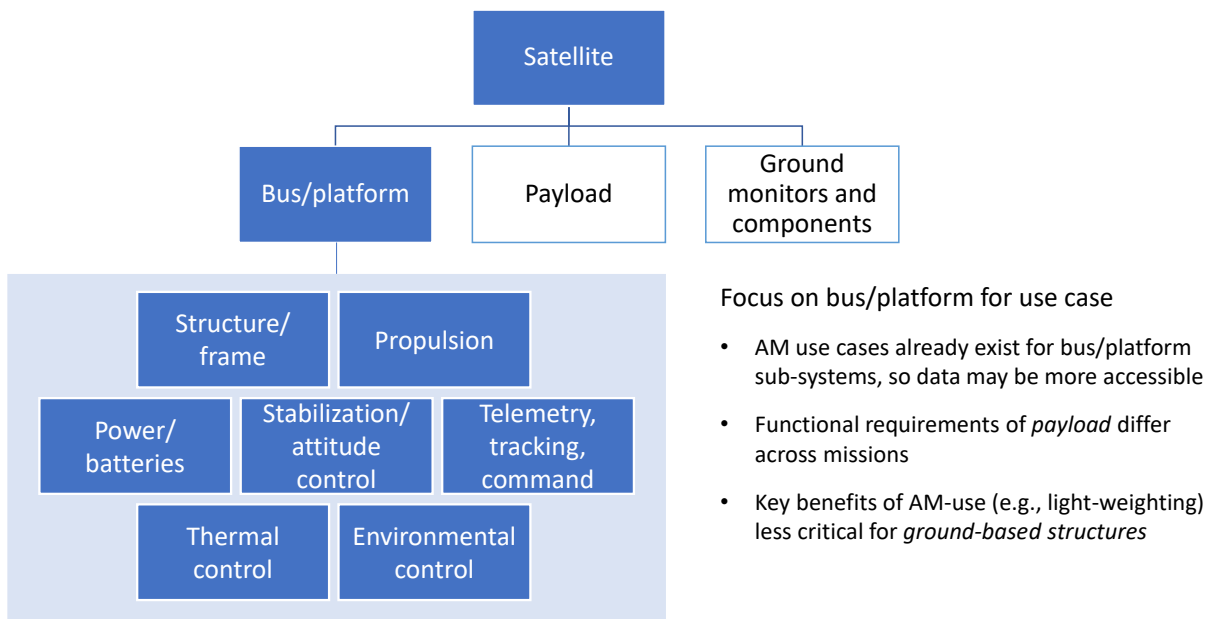


Figure 13 Satellite structure

For this use case, our key objective is to demonstrate and validate the applicability of the Decision Engine to satellite design decisions. Hence, we focused on the bus platform subsystem – specifically mounting brackets which are well-suited for topological optimization – as there already exist AM use cases for which data is more accessible (Figure 14).

The requirements breakdown process for bus platform components is also comparable across satellite types (though specific values and thresholds can differ), and the methodology set out is generally applicable to different classes of satellites. For the other two subsystem components, a similar process (supplemented by relevant data) can also be adopted to evaluate the feasibility of AM use.

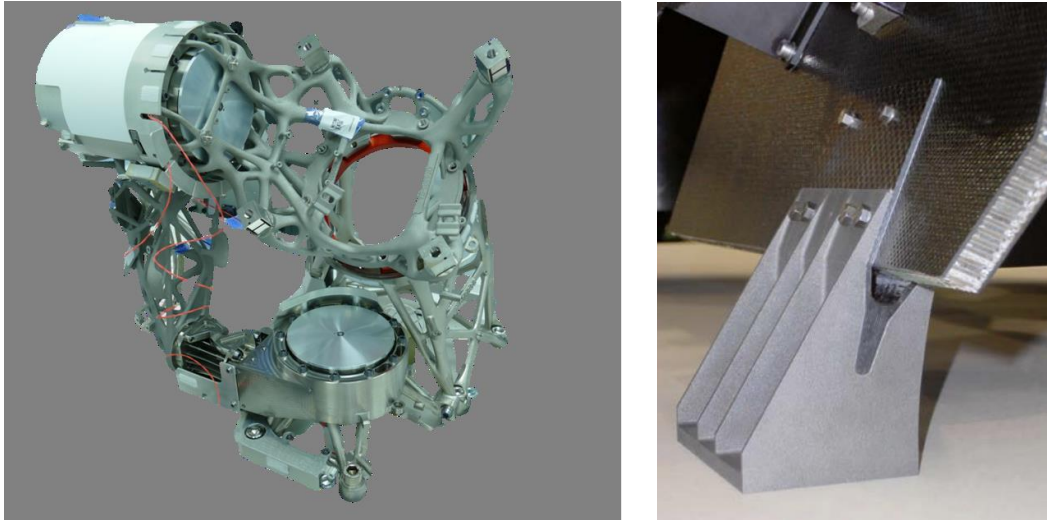
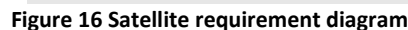


Figure 14 Use cases of AM for satellite components
(Left) AM bracket/gimbal assembly for a satellite electrical thruster (3D Systems, *Design and Additive Manufacturing Expertise from 3D Systems to Serve Thales Alenia Space Satellite Sub-System*).
(Right) AM bracket connecting satellite body to reflectors (Airbus).

1.9 MAP OUT MISSION OBJECTIVES AND REQUIREMENTS.

The next step is to construct the requirements diagram from the mission objectives. For this use case, we examined the general mission objectives of a DoD satellite deployed in one of Earth's orbits. Our goal is to find the optimal AM machine-material pair to manufacture an AM bracket/gimbal assembly using the utility-based Decision Engine. A simple system mission requirements diagram (Figure 15) was constructed using the CAMEO Magic System of Systems Architect program. The umbrella system requirements packages include the FAA satellite design and operations requirements, personnel safety, quality assurance and quality control for additive manufacturing techniques, part inventory management and planning, and satellite functionality and structural requirements. Quality assurance and control (QA/QC) requirements for AM-manufactured parts were adapted from existing standards, such as the NASA AM 6030 Handbook ("NASA-STD-6030: Additive Manufacturing Requirements for Spaceflight Systems")(Figure 16).

Component-level functionality and structural requirements were adapted from that of the Thales Alenia Space Spacebus NEO satellite Electrical Thruster Mechanism (Figure 16). Depending on the detailed mission objectives (e.g., military, navigation, remote sensing satellite, communications), further mission-specific requirements may be added under the satellite requirements package. The satellite requirements were further broken down into performance, cost, and time requirements.



Cleared for Public Release

#	Name	Text
1	☒ 1 Personnel Safety Compliance	The client will maintain employee manufacturing and assembly safety standards provided by FAA and internally
2	☒ 2 Project Schedule Compliance	The Client will ensure that the project schedule will be followed and satisfied at all times, and all changes in schedule will be clearly documented and altered when necessary
3	☐ ☒ 3 Inventory Management and Planning	The Client will ensure constant availability of tools, raw materials, and parts for the design, testing, and assembly of the satellite. Client will also ensure that there is real-time data on stock inventory
4	☒ 3.1 Raw Material Availability	Supplier shall ensure available raw materials at any stage
5	☒ 3.2 Part Manufacturing Allocation	Client shall assign in-house and outsourced manufacturing of satellite parts
6	☐ ☒ 4 Quality Assurance/ Quality Control	The client shall deliver safe, sustainable, and reliable satellite systems that are additively manufactured and adhere to FAA policy and regulations
7	☒ 4.1 AMCP (Additive Manufacturing Control Plan)	The CEO responsible for the design, acquisition, and conformance of AM hardware shall submit a consolidated AMCP addressing all applicable AM processes for review and approval by the responsible NASA program or project, with concurrence from the responsible NASA M&P organization, that does the following: a. Documents the means of conformance and method of implementation for each of the requirements of this NASA Technical Standard and NASA-STD-6033 (see section 4.5 of this NASA Technical Standard). b. Documents and provides rationale for any tailoring of the requirements of this NASA Technical Standard. c. Provides for complete governance for the implementation of AM on the program or project such that, once approved, the AMCP becomes the controlling document for implementation and verification of AM requirements of this NASA Technical Standard.
8	☒ 4.2 AM Material Classification	The CEO shall assign a primary classification (i.e., Class A, B, or C) to all AM parts in accordance with the content of Figure 4.
9	☒ 4.3 AM Decision Engine	The AM Decision Engine should be used to determine the maximum utility, appropriate AM technology, and material to use
10	☐ ☒ 5 Satellite Functionality Requirement	Satellite shall satisfy the below functionality requirements
11	☐ ☒ 5.2 Pointing Accuracy	The satellite shall have a pointing accuracy of x degrees
12	☐ ☒ 5.3 Satellite Response Time	Satellite shall have a response time of x
13	☐ ☒ 5.4 Satellite Anti-Hijack system	Satellite shall have an Anti-Hijack system to protect it from foreign interference
14	☐ ☒ 5.6 Satellite Thermal Protection System	The Satellite thermal system shall verify or regulate that all components are within an acceptable thermally operational range
15	☐ ☒ 5.6.1 Plasma Generation	The shape of the TPS shall not be such that it creates electromagnetic interference where vital to mission success
16	☐ ☒ 5.7 Guidance, Control, and Flightpath Requirement	Satellite shall have system for guidance, control, and flightpath
17	☐ ☒ 5.8 Electronic Requirement	All electronic subsystems shall perform their function for the required domain of missions in the conditions found therein
18	☐ ☒ 5.8.1 Communication Systems	The communication systems should allow for communication with ground control under as much of the flightpath as practicable
19	☐ ☒ 5.9 Satellite Survivability Requirements	The vehicle shall meet the desired survivability threshold against soft and hard-kill countermeasures
20	☒ 5.9.1 Electronic Warfare Resistance	The satellite system will be resistant to soft kill attempts via electronic warfare
21	☒ 5.9.2 Exoatmospheric Maneuverability	The vehicle will be maneuverable enough to avoid high-altitude interceptors
22	☒ 5.9.3 Low Earth Orbit Maneuverability	The vehicle will be maneuverable enough to avoid low-earth orbit artificial moons in the vicinity
23	☐ ☒ 5.10 Power Requirement	Satellite shall have a power management system to ensure sufficient supply of power for operation
24	☒ 6 FAA Regulated	Client will ensure that all tasks and final product agree with FAA policy and regulations for satellite design, assembly, and operations
25	☒ 7 Project Cost Compliance	Client will complete project tasks with the defined budget
26	☐ ☒ 32 Satellite Structural Requirements	The body of the satellite shall be capable of surviving the mission environment and satisfying non-structural requirements whilst having sufficient internal volume for all necessary sub-systems
27	☒ 32.2 Load Capacity	The vehicle shall be capable of g-force loads associated with maneuvering launch and orbital flight
28	☒ 32.3 Payload Deployment	The satellite structure shall support the successful payload deployment
29	☒ 32.4 Shaping	The external shape should adhere as closely as possible to the optimal geometry given domain of flight while meeting other system requirements
30	☐ ☒ 32.5 Maneuverability	The satellite shall be capable of executing all necessary maneuvers for the desired mission profiles
31	☐ ☒ 32.5.1 Bracket Gimball Performance Requirements	The satellite gimball structure shall satisfy performance requirements to be additively manufactured according to the required specifications
39	☒ 32.5.2 Time and Schedule Requirements	The time required for production including manufacturing, post-processing, and assembly of required Gimbals for the satellite system will be no more than 30 days.
40	☐ ☒ 32.6 Payload Capacity	Satellite shall be able to support a payload capacity of minimum x and maximum of z
41	☐ ☒ 32.7 Control Surfaces	The vehicle shall possess control surfaces with sufficient authority for LEO and GEO maneuvers required by mission profiles
42	☐ ☒ 32.8 Thrusters	The satellite structure shall endure thrust forces of up to x

Figure 17 Requirements table for a satellite mission

- “Shall” denotes requirements that must be met and will need formal verification.
- “Should” denotes a strong recommendation or a suggestion to make formal verification of another requirement easier. Failure to adhere to “should” statements often will limit launch opportunities.
- “Will” denotes a situation that will happen regardless of inputs from the launch vehicle and or/spacecraft developer. ‘Will’ statements indicate events for which the spacecraft developers should prepare.
- “Note” is a recommendation or advice to aid the CubeSat developer.

1.10 CONSTRUCT UTILITY FUNCTIONS

Next, utility functions for each attribute were constructed based on the requirements diagram. For ease of implementation, we chose linear functions that were either monotonically increasing or decreasing between the minimum and maximum desired thresholds for this demonstration use case. It is nevertheless feasible to replace these with non-linear utility functions (e.g., concave, convex, piecewise) to reflect more complex user preferences as informed by suitable data (e.g., from stakeholder surveys). The detailed attributes and min-max bounds of the linear utility functions used in this use case are set out in Table 4, with relevant sources and assumptions indicated in the table footnotes.

Table 4 Performance, cost, and production time requirements

Type	Attributes (units)	Requirement [1]
Performance	Size (mm x mm x mm)	Min: 480 x 480 x 380 [2]
	Density (g/cm ³)	Min: 1.4 (ideal) Max: 8.0
	Yield strength (MPa)	Min: 270 Max: 1,280 (ideal)
	Young's modulus (GPa)	Min: 10 Max: 290 (ideal)
	Ductility / plastic elongation (%)	Min: 0 (ideal) Max: 12
	Working temperature (°C)	Min: 128 [3]
Cost (per 1,000 parts)	Total budget (\$) <i>(includes machine, material, post-processing, testing, overheads, and launch costs)</i>	Max: 12,000,000 [4]
Production time (per 1,000 parts)	Time limit (days) [5]	Max: 30 [6]

^[1](Yasaka and Onoda)

^[2](3D Systems, *Design and Additive Manufacturing Expertise from 3D Systems to Serve Thales Alenia Space Satellite Sub-System*)

^[3](Plante and Lee)

^[4]Arbitrary bound

^[5](Airbus)

^[6]Arbitrary limit, with estimated relative time savings for AM/TM options for 1,000 parts

We ran the Decision Engine on four machine-material alternatives:

- AM option 1: DMP Factory 500 + LaserForm Ti Gr23 (titanium alloy)
- AM option 2: Renishaw AM250 + AlSi10 Mg-0403 (aluminum alloy)
- AM option 3: Renishaw AM250 + SS 316L-0407 (stainless steel)
- Traditional manufacturing (TM) option: Forging + Ti64 (titanium alloy)

The performance attributes (Table 5) of each machine-material pair depend mostly on machine-material properties and are hence relatively component-agnostic. On the other hand, the cost

and production time attributes (Table 6 and Table 7) depend on component specifications, including the physical and batch sizes. These were approximated based on past case studies and some simplifying assumptions (e.g., cost and time reduction achievable through AM adoption) to demonstrate the logic of the Decision Engine. Replacing these values with more accurate data is straightforward, so using approximate data here does not compromise the applicability of the Decision Engine.

Table 5 Machine-material performance ranges

Attribute (units)	AM: DMP Factory 500 [7] -LaserForm Ti Gr23 (A) [8]	AM: Renishaw AM250-ALSi10Mg-0403 [5], [11]	AM: Renishaw AM250-SS 316L-0407[9], [10]	TM: Forging-Ti64 [12], [13]
Size (mm x mm x mm)	500 x 500 x 500	250 x 250 x 365	250 x 250 x 365	1300 x 1300 x 1300 [14]
Density (g/cm ³)	4.42	2.68	7.99	4.43
Yield strength (MPa)	1030 – 1160	200 – 266	480 – 550	880
Young's modulus (GPa)	114 – 122	66 – 76	180 – 201	114
Ductility / plastic elongation (%)	7 – 13	4 – 10	27 – 45	10
Max working temperature (°C)	427 – 595 [15]	570 – 590	1371 – 1399	427 – 595 [12]

^[7] (3D Systems, *DMP Factory 500 Scalable Metal Additive Manufacturing for Seamless Large Parts*)

^[8] (*LaserForm® Ti Gr23 (A)*)

^[9] (*SS 316L-0407 Powder for Additive Manufacturing Process Specification*)

^[10] (*Renishaw AM250 Review - 3D Printer*)

^[11] (*ALSi10Mg-0403 Powder for Additive Manufacturing Process Specification*)

^[12] (Laureijs et al.)

^[13] (*Titanium Ti-6Al-4V (Grade 5), Annealed*)

^[14] Smallest dimension for Ti, taken from (*Forging Capabilities Chart - Metal Alloy Chart*)

^[15] (ASM International)

Table 6 Machine-material cost breakdown (1,000 parts)

Cost component	AM: DMP Factory 500-LaserForm Ti Gr23 (A)	AM: Renishaw AM250-ALSi10Mg-0403	AM: Renishaw AM250-SS 316L-0407	TM: Forging-Ti64 [16]
Total budget	9,374,000	5,687,000	14,166,000	10,400,000
Machine	550,000 [17]	110,000 [16]	110,000 [18]	400,000
Material	544,000 [19]	57,000 [21]	126,000 [20]	
Post-processing, testing, maintenance	320,000 [22]	320,000 [20]	320,000 [20]	
Overheads	960,000 [23]	960,000 [21]	960,000 [21]	
Launch cost [24]	7,000,000	4,240,000 [23]	12,650,000 [25]	10,000,000

^[16] (Laureijs et al.)

^[17] (*Metal 3D Printing: The Manufacturing & Design Guide*) – Average DMLS price

^[18] (*Renishaw AM250 Review - 3D Printer*)

^[19] (Laureijs et al.) – 42% of DMLS per bracket cost, x1,000

- ^[20] (MSE Supplies, *316L Iron Based Stainless Steel Metal Powder for Additive Manufacturing*) – Assumes mass scales as the weighted ratio of density as benchmarked to Ti option, \$90/kg of powder, and 90% yield/recyclability
- ^[21] (MSE Supplies, *AlSi10Mg Aluminum Based Metal Powder for Additive Manufacturing (3D Printing)*) – Assumes mass scales as the weighted ratio of density as benchmarked to Ti option, \$120/kg of powder, and 90% yield/recyclability.
- ^[22] (Laureijs et al.) – 10% of DMLS1 cost, x1,000
- ^[23] (Laureijs et al.) – 30% of DMLS1 cost, x1,000
- ^[24] Assumes 1kg per bracket, 30% mass reduction from topological optimization for AM case, and \$10,000 to launch 1kg into orbit.
- ^[25] Assumes mass scales as the weighted ratio of density as benchmarked to Ti option, and \$10,000 to launch 1kg into orbit.

Table 7 Machine-material production time (1,000 parts)

Attribute (units)	AM: DMP Factory 500-LaserForm Ti Gr23 (A)	AM: Renishaw AM250-AlSi10Mg-0403	AM: Renishaw AM250-SS 316L-0407	TM: Forging-Ti64
Time limit (days) [26]	20	20	20	25

^[26] (Airbus)

1.11 RESULTS: DECISION ENGINE RECOMMENDATIONS

The data and utility functions from the previous section were provided as input to the Decision Engine. Assuming equal importance of performance, cost, and time attributes (i.e., each with a weightage of ~33%), the Decision Engine recommended AM option 2 (aluminum alloy) (Figure 18). This is largely attributable to the aluminum alloy having a much lower density and hence estimated launch cost compared to the other options.

On the other hand, if the decision-makers were relatively cost-insensitive, but production time was instead the most important attribute (e.g., to meet stringent launch window requirements) – say at 50% weightage – AM option 1 (titanium alloy) would edge out the other alternatives as the best option (Figure 19). This was also, in fact, the machine-material used for the Spacebus NEO satellite Electrical Thruster Mechanism, on which this use case was based. The TM option scored the lowest since it was assumed to have a 25% longer production time (for 1,000 parts) due to additional lead time for mold construction and tooling. (Note: the production time disadvantage for TM usually goes away as the number of parts increases, and TM could have a production time advantage at high build volumes.) AM option 1 performed better than the other AM options as titanium had more desirable material properties for this particular application (e.g., high strength-to-density ratio), and the DMP machine is able to print larger parts.

In some cases, there may be “hard constraints” for which certain manufacturing options are a no-go unless these are satisfied. For example, component size could be a hard constraint if the design has been finalized and redesigning a single part as an assembly of smaller sub-parts is not possible or undesirable. When the component size was implemented as a “hard constraint,” options using the Renishaw AM250 machine were ruled out (i.e., utility collapses to zero) since

the machine is unable to produce parts of a sufficiently large size (**Error! Reference source not found.**). (Note: the operating temperature was also implemented as a hard constraint here, but this had no impact on the recommendation output as all the options met this hard constraint.)

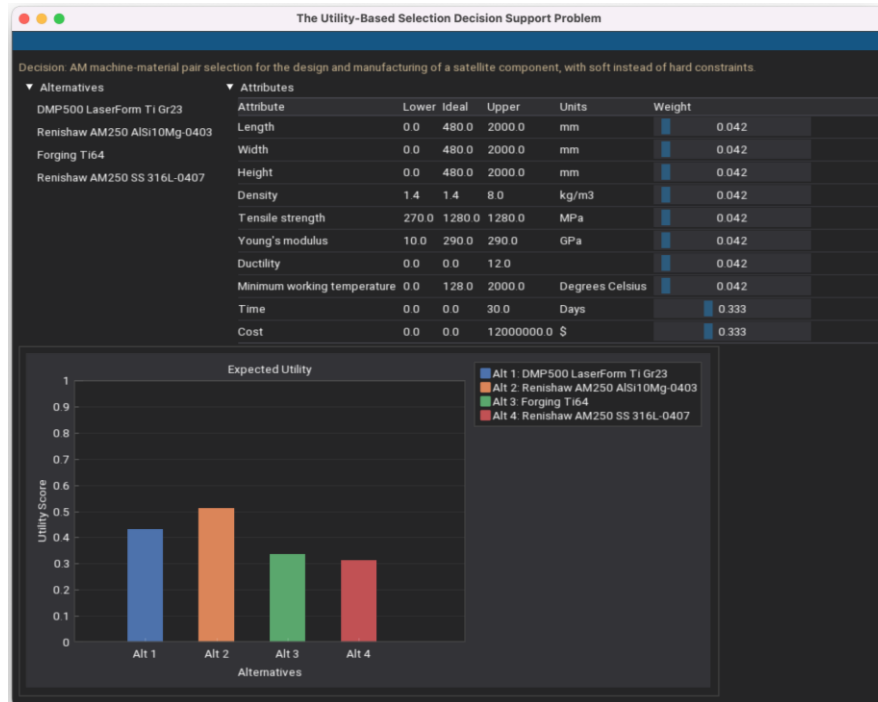


Figure 18 Decision Engine recommendation based on equal attribute weightage (performance, cost, time)

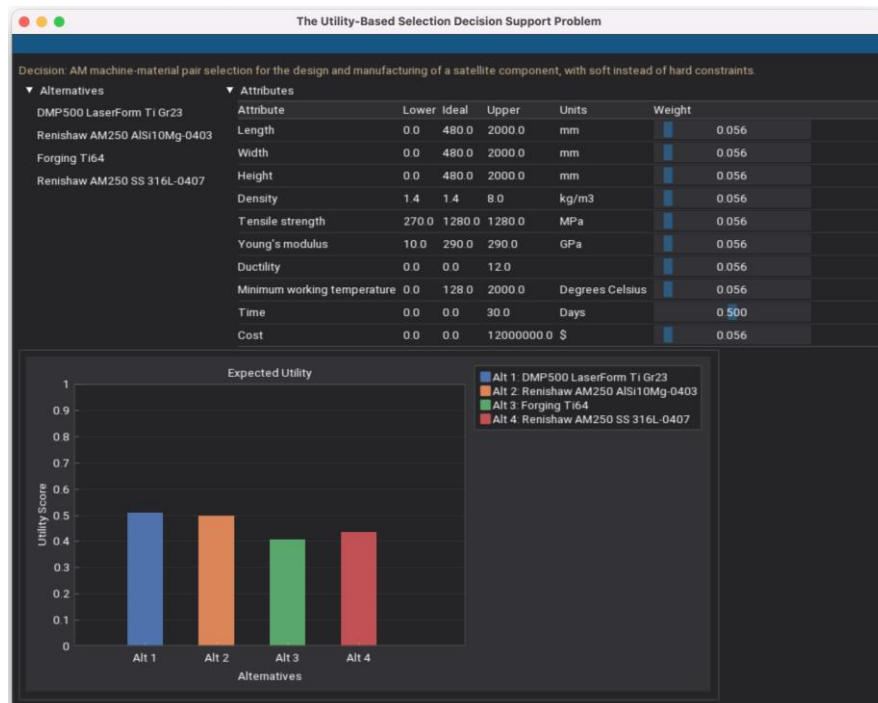


Figure 19 Decision Engine recommendation with production time being the most important attribute (50% weightage)

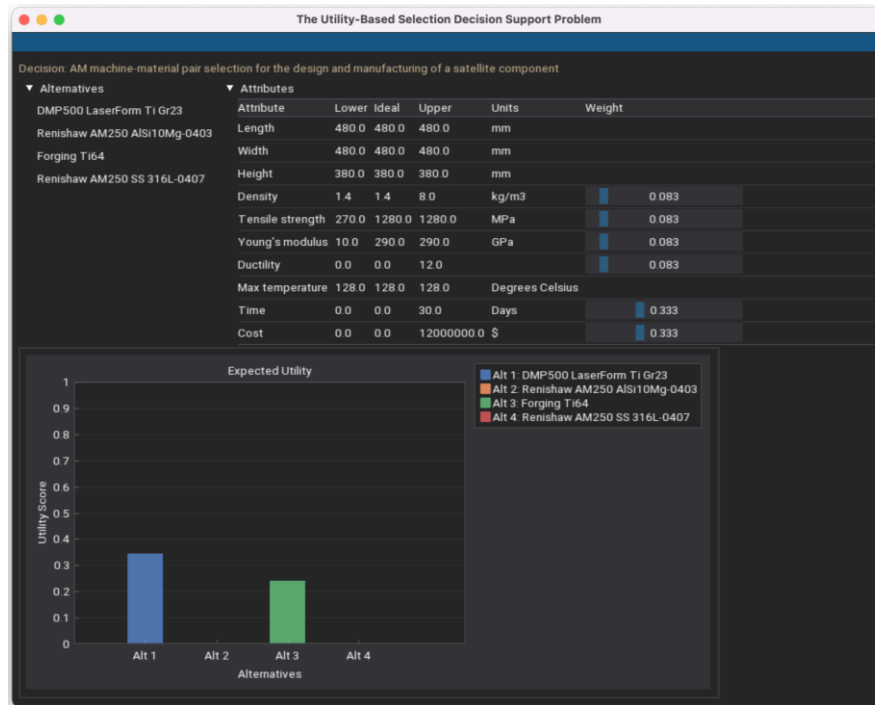


Figure 20 Decision Engine recommendation with component size as a “hard constraint”

1.12 SUMMARY/FUTURE WORK

Use case 2 has demonstrated how the Decision Engine can be integrated into the mission engineering process of designing and manufacturing satellite components – specifically to identify the optimal machine-material pair for an AM component. Decision-makers often also need to tackle “manufacturability” considerations at a portfolio level. In future work, the Decision Engine can be enhanced to support AM-use decisions pertaining to a portfolio of parts (e.g., which combinations of AM options best support the production of a variety of satellite or spacecraft parts). In addition, as portfolio selection problems are likely to involve more stakeholders, the Decision Engine interface can also be expanded to be customizable for different decision-makers (e.g., project manager vs. component engineer) to support hierarchical decision-making within an organization.

Use Case 3: Design, Manufacturing, and Maintenance of Aircraft Components

1.13 BACKGROUND/OVERVIEW

Virginia Tech was approached by a large aerospace original equipment manufacturer (OEM) looking to leverage additive manufacturing (AM) to replace damaged, out-of-production parts for fleet sustainment. Specifically, this OEM is looking for a means for producing 100 replacement aileron bellcranks on a legacy aircraft. Traditionally made through metal casting, the original part

supplier has discontinued production. Because the continuous operation of the fleet is critical, the company is eager to find a new means of sourcing the part quickly. In this transition period, the company is interested in assessing the utility of the traditional manufacturing metal casting approach against those of metal additive manufacturing methods, as additive manufacturing typically has lower lead times and supply chain costs (Gradl et al.). The goal of this use case study is to apply the decision engine to compare the utility of several manufacturing approaches for low-volume production of a custom aircraft part for fleet sustainment. The information of this use case was adapted from past collaborative work with the OEM, and thus the simulated decisions represent an example of a real issue modern companies may face with respect to the desire to cut rising costs and/or sourcing parts that have become obsolete on the market.

1.14 PROBLEM STATEMENT

The original design of the bellcrank is shown on the left side of Figure 21. The dimensions of the bellcrank used in this case study have been augmented from the actual part so as to protect the OEM's intellectual property. The decision engine is used to evaluate the utility of producing these parts using *traditional metal casting* and several different additive manufacturing solutions, including:

- *Hybrid wire arc additive manufacturing (hWAAM)*: In this hybrid process, a wire arc welding head selectively deposits metal in a layer-wise fashion. A CNC milling spindle selectively removes material at each layer to refine the part quality and surface finish. Following fabrication, the fully dense metal part needs moderate heat treatment prior to use.
- *Metal binder jetting (mBJT)*: In this process, the binder is selectively ink-jetted into a metal powder bed to fabricate a green part. Following printing, post-processing steps include binder curing, part de-powdering, binder pyrolysis, and metal sintering.
- *Sand Binder Jetting (sBJT)*: In this process, binder jetting is used to 3D print molds from foundry sand. Following printing, the printed molds are de-powdered and assembled for traditional metal casting processing.
- *Metal laser powder bed fusion (L-PBF)*: In this process, a laser selectively melts the metal powder in a layer-wise fashion. The printed part is fully dense and can be inserted into the application following post-processing steps, including de-powdering, heat treatment, support removal, and surface finishing.

This case study is separated into two decision scenarios as follows:

- **Scenario 1: Part Replication.** In the first scenario, the company is comparing the utility of different manufacturing techniques to produce 100 replicates of the bellcrank geometry using 6061 Aluminum. In this decision, the company is only evaluating alternative manufacturing processes to replicate the same geometry and material as in the original design shown on the left side of Figure 21.

- **Scenario 2: Topology Optimized Re-design versus Original Design.** In the second scenario, the company is evaluating the utility of different manufacturing techniques to produce 100 re-designed bellcranks, which have been optimized for lightweighting. Specifically, topology optimization software (*Autodesk Fusion 360*) has been employed in which part mass is generatively removed from the original design as guided by an iterative evaluation of the stresses within the part (Shanmugasundar et al.). The optimization algorithm sought to minimize part mass while still retaining sufficient part stiffness to meet the load specifications. The resulting topology optimized geometry is shown on the right side of Figure 21. In this scenario, the effects of a change in part geometry enabled by additive manufacturing are explored while the material (Aluminum 6061) is held constant.

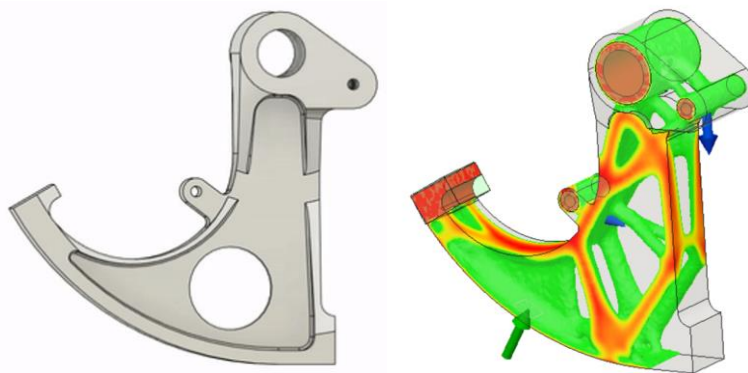


Figure 21 Aileron bellcrank

(Left) CAD model of the original aileron bellcrank. The bellcrank is traditionally manufactured through the traditional metal casting of 6061 Aluminum.

(Right) Topology optimization was used to redesign the aileron bellcrank for mass minimization. Colored regions indicate where material should be placed within the volume. Red regions represent regions of high stress; green regions represent areas of low stress. The material used in the optimization is the same as that in the original design, 6061 Aluminum. The grey bounding box around the optimized geometry is included to illustrate the mass savings enabled by topology optimization.

Attributes

In decreasing order of importance, the customer is concerned with the minimization of cost, time, and part mass. These customer concerns form the attributes of the decision. In addition to these customer concerns, part bounding box size was added as an attribute to ensure that the part could fit within the allowable build volume of each additive manufacturing process. Thus, the attributes of the decision are part bounding box size, total cost, total time, and part mass.

Utility Functions

Utility functions generated for each attribute are shown in Table 8. A minimum point, an intermediate point, and a maximum point were used to fit the functions. A utility function was not fitted for the part bounding box attribute. Instead, this function had the form of a binary “on/off” condition where, if the bounding box volume of the manufacturing process being considered is below the requirement, the utility of that process is zero regardless of the utility values.

For the *total cost*, a monotonically decreasing linear function was chosen because utility for the customer decreases proportionally as manufacturing cost increases. For both *total time* and *part mass*, a concave function was chosen because utility for the customer decreases more sharply as each of these attributes increases. The utility functions are summarized in Table 8. Figure 22, Figure 23, and Figure 24 show the points used to fit utility functions for cost, time, and mass, respectively. In these figures, please note that the data points were obtained from customer surveying.

Table 8 Utility Functions

Attribute	Utility Function Type	Utility Function: $u(x) = a + bx + ce^{dx}$			
		a	b	c	d
Part Bounding Box (mm x mm x mm)	On/Off	-	-	-	-
Total Cost (\$)	Linear	1	-2e-6	0	0
Total Time (hours)	Exponential (Concave)	0	0	1.002	-0.00198
Mass (kg)	Exponential (Concave)	0	0	1.019	-0.41000

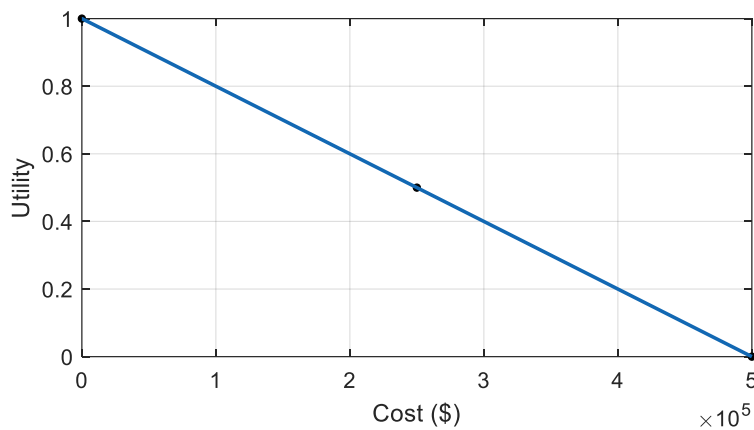


Figure 22 Fitted utility as a function of cost

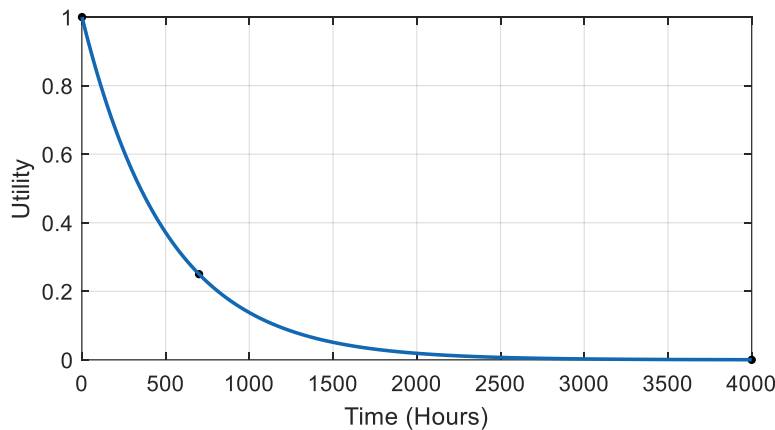


Figure 23 Fitted utility as a function of time

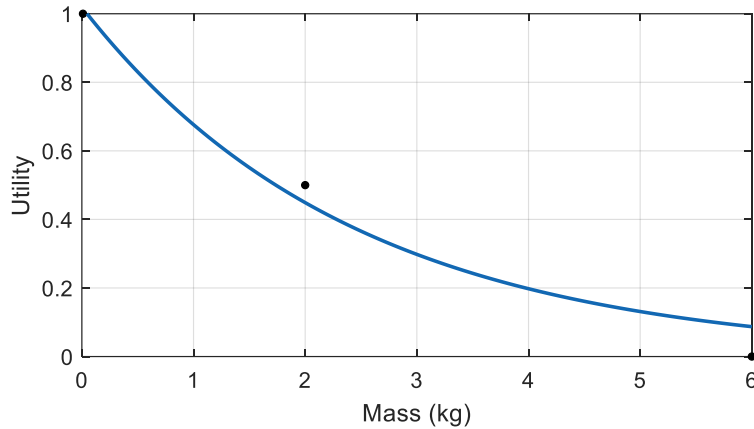


Figure 24 Fitted utility as a function of mass

A weight was assigned to each attribute's utility function to represent the customer's preferences of the relative importance of each attribute. In Scenario 1, in which manufacturing processes are evaluated for their utility to replicate the original part geometry and material, the customer has a slightly stronger preference for reducing cost than time. On the other hand, in Scenario 2, in which the utility of replicating the original part geometry via metal casting is compared to the additive manufacturing processes' ability to fabricate the topology optimized part geometry (Figure 21, right), the customer has near equal preference for minimizing cost, time, and part mass. These weighting values are shown in Table 9.

Table 9 Weights of attributes generated from customer requirements

Attribute	Scenario 1: Weight	Scenario 2: Weight
Total Cost	0.6	0.4
Total Time	0.4	0.3
Mass	-	0.3

1.15 DECISION ENGINE DATA INPUTS

Part Bounding Box

The bounding box size of the part was obtained by measuring the length, width, and height of the part's computer-aided design (CAD) model. The bounding box of the bellcrank measures 350 mm x 350 mm x 87 mm; thus, the requirements for this attribute are these dimensions. The bounding box size is the same for both scenarios.

Total Cost

Cost estimates for traditional metal casting were obtained from a vendor's website (Liaoning Borui Machinery Co.). The estimated cost for manual green sand casting of a large complex shape is \$2,500 per part. Cost estimates for the additive manufacturing processes were generated by a cost model from *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing* (Gibson et al.) given by:

$$Cost = P + O + M + L$$

Where P is the pro-rated machine purchase cost, O is the machine operation cost, M is the material cost, and L is the labor cost. In order to calculate these four sub-costs, information on part geometry, material specification from suppliers, and machine process parameters are needed. At a high level, the model first uses part geometry information to calculate total scan length (the total linear distance traveled by the print head during fabrication), which is estimated from the part volume, the average cross-sectional area of each layer, and deposition diameter. The estimated scan length is then used in combination with known process parameters (i.e., scan speed, deposition head diameter, and layer height.) to estimate the total part build time. Once the build time is obtained, estimates for the cost of machine purchase, operation, materials, and labor can be calculated. Process parameters were sampled from works in literature for each manufacturing process. Process parameters for hWAAM were adapted from (Shi et al.). Process parameters for binder jetting were adapted from (Bai et al.). Process parameters for powder bed fusion were adapted from (Uddin et al.). Cost estimates were rounded to the nearest hundred dollars, and an error of $\pm 10\%$ in estimated cost is assumed in order to account for discrepancies.

Total Time

Times estimates for traditional metal casting were obtained from information published on the Impro website (Impro). Time estimates for the additive manufacturing processes were calculated using build time models from *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing* textbook (Gibson et al.). Build time is estimated from the total printing scan length and process parameters specific to each additive manufacturing process, such as layer height, hatch spacing, deposition head diameter, and scan speed. Values for hWAAM process parameters were adapted from (Shi et al.). Values for binder jetting process parameters were adapted from (Bai et al.). Values for powder bed fusion process parameters were adapted from (Uddin et al.).

In addition to machine build time, the time required for human hands-on labor, which includes printer facilitation and post-processing, is accounted for in each process. The estimated human time varies for each process and depends on the process and post-processing needs. The pertinent assumptions are listed in Table 10 and Table 11 for Scenario 1 and Scenario 2, respectively.

Part Mass

The part mass is obtained from the CAD model of the bellcrank. In Scenario 1, since the part design and material are unchanged from that of the original, the part mass produced by each process is the same as the original part, 4.02 kg.

In Scenario 2, the additive manufacturing processes' utility is reevaluated for their ability to fabricate topology optimized design with reduced mass (Figure 21, right). According to Maurer, topology optimization can be used to reduce the mass of components by up to one-third (Maurer). Thus, the topology optimized design has an estimated part mass of 2.68 kg. The more complex geometry generated from topology optimization is not manufacturable using traditional

metal casting, and thus the part mass for the casting process is kept at 4.02 kg. An uncertainty of 1% in mass is assumed to account for discrepancies and tolerances in manufacturing.

Table 10 Data Inputs for Scenario 1

(Uncertainty assumptions: $\pm 10\%$ for cost and time, $\pm 1\%$ for mass)

Attribute (units)	Requirement	AM: hWAAM DMS 2Cubed Al6061 [27]	AM: Binder Jet ExOne X160Pro Al6061 [28]	AM: Binder Jet ExOne X160Pro Sand+Al6061	AM: PBF DMP Factory 500-LaserForm Al6061 [29], [30]	TM: Casting Al6061
Part Bounding Box (mm x mm x mm)	87 x 350 x 350	610 x 610 x 610	800 x 500 x 400	800 x 500 x 400	500 x 500 x 500	-
Parts per batch (no.)	-	6	8	5	5	-
Part Mass (kg)	-	4.02	4.02	4.02	4.02	4.02
Total Cost (\$)	\$100,000	\$34,600	\$98,500	\$58,900	\$164,100	\$250,000 [31]
Prorated Machine Cost (\$)	-	\$1,000	\$500	\$800	\$5,700	-
Operation Cost (\$)	-	\$11,800	\$5,700	\$9,100	\$51,700	-
Materials Cost (\$)	-	\$9,800	\$85,100 [32]	\$32,800	\$90,500 [32]	-
Labor Cost (\$)	-	\$11,900	\$7,300	\$16,200	\$16,200	-
Total Time for 100 Parts (hours)	900	930	774	1,377	2,186	2,000 [33]
Machine Time (hours) [34]	-	590	566	915	1,724	-
Human Time (hours)	-	340 [35]	208 [36]	462 [37]	462 [38]	-

[27] 2Cubed printer information from (Diversified Machine Systems)

[28] X160Pro printer information from (*ExOne X1 160PRO Review - Industrial Metal and Ceramic 3D Printer*)

[29] Factory-500 printer information from (GF Machining Solutions)

[30] (Uddin et al.)

[31] Sand mold cost estimate from (Liaoning Borui Machinery Co.)

[32] (MSE Supplies, *6061 Aluminum Based Metal Powder for Additive Manufacturing*)

[33] (Impro Precision)

[34] (Gibson et al.)

[35] Estimate roughly 10 hours of post-processing per batch of printed parts. Includes time for print set up, part removal, and finishing machining

[36] Estimate roughly 15 hours of post-processing per batch of printed parts. Includes time for print set up, de-powdering, and time to set up curing and sintering of parts

[37] Estimate roughly 22 hours of post-processing per batch of printed parts. Includes time for print set up, de-powdering, curing, and casting

[38] Estimate roughly 8 hours of post-processing per batch of printed parts. Includes time for print set up, part removal, and machining

Table 11 Data Inputs for Scenario 2

(Uncertainty assumptions: $\pm 10\%$ for cost and time, $\pm 1\%$ for mass)

Attribute (units)	Requirement	AM: hWAAM DMS 2Cubed Al6061	AM: Binder Jet ExOne X160Pro Al6061	AM: Binder Jet ExOne X160Pro Sand+Al6061	AM: PBF DMP Factory 500- LaserForm Al6061	TM: Casting Al6061
Part Bounding Box (mm x mm x mm)	87 x 350 x 350	610 x 610 x 610	800 x 500 x 400	800 x 500 x 400	500 x 500 x 500	-
Part Mass (kg)	4.02	2.68 [39]	2.68 [39]	2.68 [39]	2.68 [39]	4.02
Total Cost (\$)	\$100,000	\$31,300	\$79,000	\$48,000	\$134,000	\$250,000
Prorated Machine Cost (\$)	-	\$1,000	\$500	\$800	\$5,700	-
Operation Cost (\$)	-	\$11,800	\$5,700	\$9,100	\$51,700	-
Materials Cost (\$)	-	\$6,500	\$56,700	\$21,900	\$60,400	-
Labor Cost (\$)	-	\$11,900	\$7,300	\$16,200	\$16,200	-
Total Time for 100 Parts (hours)	900	930	774	1,377	2,186	2,000
Machine Time (hours)	-	590	566	915	1,724	-
Human Time (hours)	-	340	208	462	462	-

^[39] (Maurer)

1.16 RESULTS: DECISION ENGINE RECOMMENDATIONS

Scenario 1: Part Replication

The attribute weights, attribute data, and utility functions were input into the decision engine in order to calculate the utility of each manufacturing process for Scenario 1. The Scenario 1 data inputs for the decision engine are summarized in Table 10. The expected utility of each process is plotted in the bar graph in Figure 25.

It is observed from these results that traditional casting has the lowest utility (0.31), while hybrid wire arc additive manufacturing (hWAAM) has the highest utility (0.62). This result follows expectations, as the total cost and time for hWAAM are lower than those of the other processes (Table 10). Because the customer prioritizes cost minimization in their attribute weighting, it is reasonable to expect a process that has a lower cost to have a higher utility.

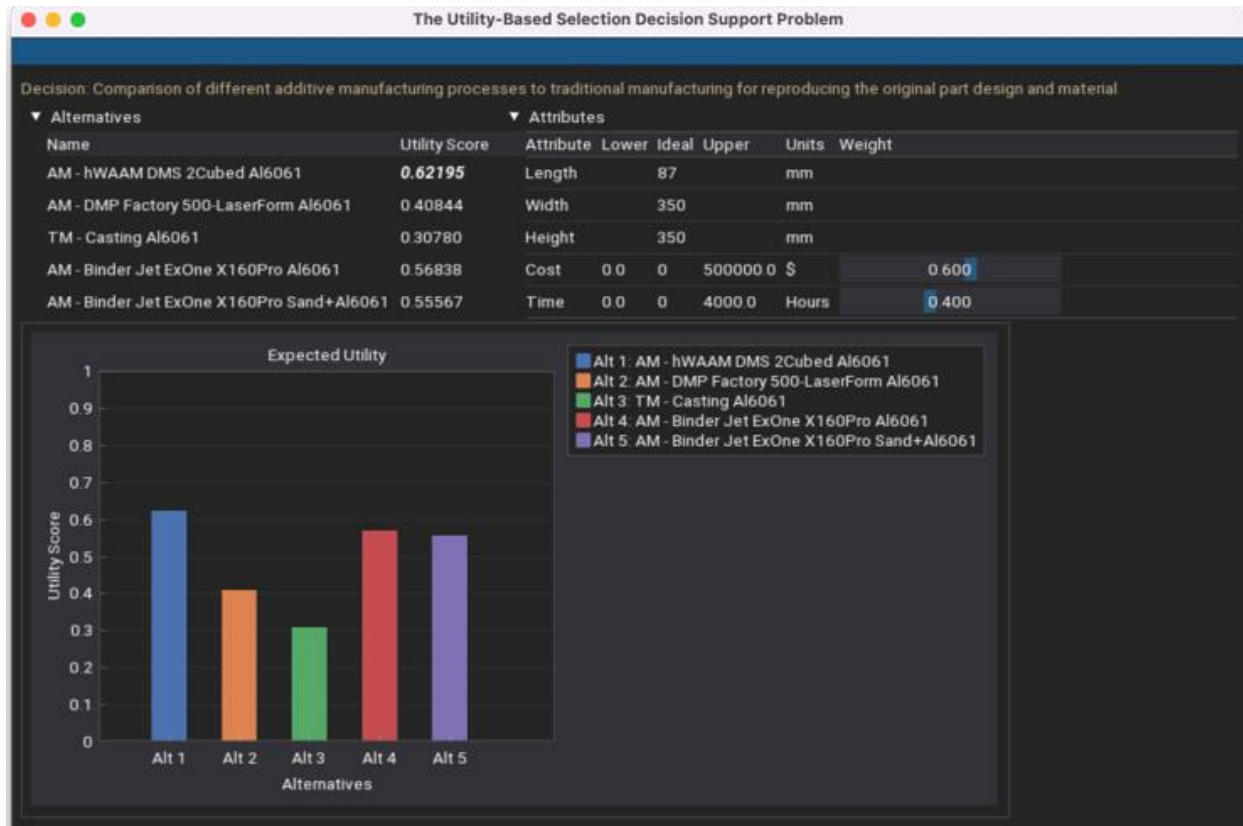


Figure 25 Decision engine outputs for Scenario 1

The expected utility of each manufacturing technique is plotted. The hWAAM process offers the highest utility, while traditional casting offers the lowest utility.

Scenario 2: Part Re-design

The attribute weights, attribute data, and utility functions were input into the decision engine in order to calculate the utility of each manufacturing process for Scenario 2. The Scenario 2 data inputs for the decision engine are summarized in Table 11. The expected utility of each process is plotted in the bar graph in Figure 26. Once again, traditional casting has the lowest utility (0.22), while hybrid wire arc additive manufacturing (hWAAM) has the highest utility (0.52).

However, note that the gap in utility between hWAAM (0.52) and binder jetting with 6061 Aluminum (0.51) has decreased significantly, suggesting that the two manufacturing processes are now comparable in this scenario. Between Scenario 1 and Scenario 2, the difference in utility between the two processes is 0.04, indicating that the introduction of topology optimization into the decision process can have an impact on recommendation output by the engine. This change is largely due to the fact that the bulk of the cost for the binder jetting process comes from the powder material feedstock, which can be quite expensive (~\$185/kg) (MSE Supplies, *6061 Aluminum Based Metal Powder for Additive Manufacturing*). However, in hWAAM, the cost of material is substantially less (~\$20/kg) as it uses conventional welding wire (*WeldingSupply 1100-116-3*).

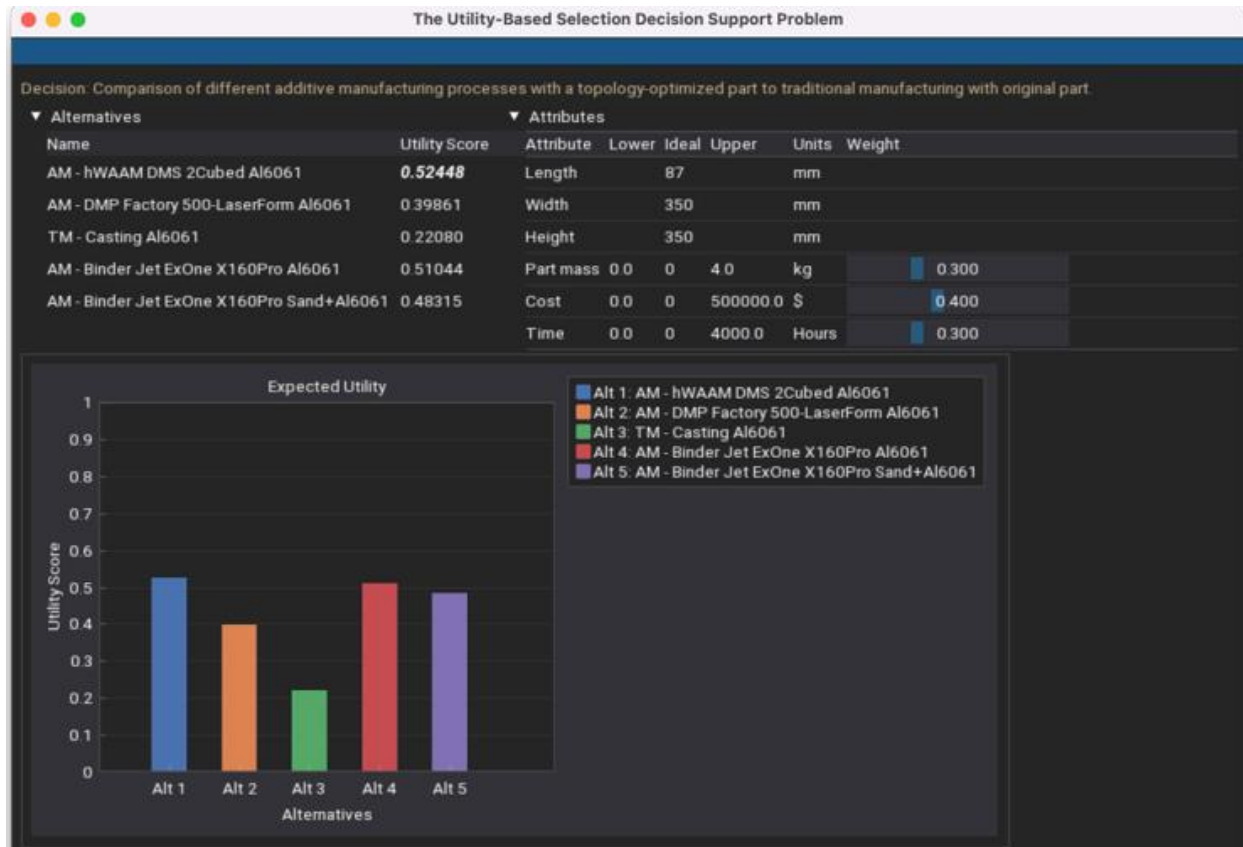


Figure 26 Decision engine outputs for Scenario 2

The expected utility of each manufacturing technique is plotted. The hWAAM process still offers the highest utility; however, due to decreased material costs from design mass reduction, the binder jetting process now has comparable utility. Traditional casting is still predicted to have the lowest utility.

Mass reduction of the bellcrank design through topology optimization has reduced the amount of material required to manufacture the part by one-third, which in turn has driven the total cost of the binder jetting process down by roughly 20%. An image of the optimized component, manufactured with hWAAM at Virginia Tech, is provided in Figure 27. Thus, this particular scenario highlights the possible changes in utility ranking of different processes as a result of subtle changes in the attributes by the introduction of topology optimization enabled in additive manufacturing processes.

1.17 SUMMARY/FUTURE WORK

In Use Case 3, a fleet sustainment decision by an aerospace company was explored. Within this decision, two possible scenarios for the design and manufacturing of an aileron bellcrank were explored. The first scenario enabled a comparison between traditional casting and different additive manufacturing processes' utilities in replicating the original bellcrank geometry and material.

In Scenario 2, the decision was re-evaluated with considerations that additive manufacturing processes can be used to produce a re-designed bellcrank geometry that was optimized for lightweighting. In both scenarios, the hybrid wire arc additive manufacturing process had the highest utility as it offered a sufficiently large build volume and offered the lowest cost and lead time among the alternatives. Between Scenario 1 and Scenario 2, a decrease in the relative ranking in utility between the two top manufacturing processes, hWAAM and binder jetting, was observed, indicating that additional consideration of additive manufacturing's ability to manufacture topology optimized parts in the decision process can impact engine outputs.

In the future, a third scenario that could be explored would be looking at how changing both the design and the material of the part for each process changes the utility. The change in material would change the design output by topology optimization, so each process/material combination would be tied to a unique design. Integration of the topology optimization process with the decision tool in an iterative fashion would also be a natural extension of this work.



Figure 27 Topology optimized bellcrank produced by hWAAM

(Note: The surface finish indicates that the AM part was post-processed using a milling machine.)

Digital Engineering Strategy

Roadmap on Creating Digital Technical Data Packages for the Adoption of Metal Additive Manufacturing

1.18 BACKGROUND/OVERVIEW

This document covers the Digital Engineering strategy focusing on adopting Metal Additive Manufacturing (AM) for the Acquisition Innovation Research Center (AIRC). According to the

Department of Defense (DoD) 2018 Digital Engineering Strategy, digital engineering is “an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines to support lifecycle activities from concept through disposal” (DoD, 2018, p. 3). The digital engineering strategy uses digital engineering principles, model-based approaches, and contemporary technologies for designing, acquiring, and sustaining products at DoD. Advantages of using a Digital Engineering strategy include improvements in engineering and acquisition process routines; capturing more consistent and traceable requirements between the OEM contractors and the DoD program engineering offices; enhanced decision-making opportunities by accessing current data; and development of a digital-first culture. DoD lists five different goals for the digital engineering strategy. Figure 28 shows the five goals of the Digital Engineering Strategy.



Figure 28 Digital engineering goals
(Department of Defense)

The second goal of the digital engineering strategy is focused on providing an **authoritative source of truth** for communication and the use of product information across various stages of the product lifecycle. This summary document focuses on developing the roadmap and data packages necessary to support the development of authoritative sources of truth for AM, and an appropriate technological infrastructure necessary to access, manage, use, and distribute the data package across the additive manufacturing supply chain. In addition to the 2018 strategy document, DoD has provided additional documentation titled ‘DoD instruction 5000.93’ for the implementation and usage of additive manufacturing in DoD (*DoD Instruction 5000.93, Use of Additive Manufacturing in the DoD*).

The DoD instruction outlines the procedures and guidance for the integration of Additive Manufacturing practices during the platform acquisition stage and the ensuing development of an AM supply chain. The instruction document calls for the establishment of qualification procedures and the development of a process that meets the acceptance criteria through the creation of common standards, specifications, and practices (DoD, 2021). For establishing a

reliable process and incorporating AM into the supply chain, the instruction document recommends the use of JAMMEX (Joint Additive Manufacturing Model Exchange) and other interoperable data management capabilities (DoD, 2021), including the development of common data standards and requirements. In addition, the instruction lists the use of common Technical Data Package standards such as MIL-STD-31000 for developing and sharing the authoritative source of truth for product information (DoD, 2021). By doing so, model-based engineering and model-based definition practices form the basis for AM adoption and the application of the DoD digital engineering strategy.

The DoD strategy and implementation plan calls for developing and using the Model-Based Engineering (MBE) tool suite for creating, managing, and using MBE practices (DoD, 2018). The goal of this document is to review the recommendations and requirements proposed by DoD for metal AM adoption and to develop a guidance document for the AIRC use case. Along with this, appropriate standards and literature were reviewed to develop the outcomes reported in this document. This supports AIRC in adopting metal AM and developing the data packages necessary for sharing with AM supply chain and sustainment of AM for the acquisition process.

1.19 METHODOLOGY

Based upon the recommendations of DoD, relevant standards and literature pertaining to metal additive manufacturing, technical data packages, and model-based definition were reviewed. The roadmap and data package for the metal additive manufacturing practices were developed by reviewing the standards and literature. Table 12 lists the various topics that have been explored as part of this review and the sources included in the review.

Table 12 Overall results from the review

Topic reviewed/covered	Source	Source type
Format for Additive Manufacturing File (AMF)	(ISO - ISO/ASTM 52915:2020, <i>Specification for Additive Manufacturing File Format (AMF) Version 1.2</i>)	Standard
Additive manufacturing data processing overview	(ISO - ISO/ASTM 52950:2021, <i>Additive Manufacturing, General Principles, Overview of Data Processing</i>)	Standard
Format for AMF and STL (stereolithography) file	(ISO - ISO/ASTM 52915:2013, <i>Standard Specification for Additive Manufacturing File Format (AMF) Version 1.1</i>)	Standard
Activities in metal AM and associated data package	(Kim, Witherell, Lipman, et al.) (Kim, Witherell, Lu, et al.) (Qin et al.)	Literature

1.20 ADDITIVE MANUFACTURING FILE FORMAT

ISO/ASTM 52915:2020 standard provides the specification for preparing an interchange format of Additive Manufacturing File (AMF). The standard recommends the use of XML for preparing and sharing product-related information. The standard provides a general structure, specification, and format for preparing AMF in XML version, including suggested data categories

and attributes. The standard lists guidelines for including geometry specification, material specification, color specification, texture specifications, constellation, and metadata of product. Figure 29 shows the basic AMF file from the ISO/ASTM 52915:2020 standard.

```
<?xml version="1.0" encoding="UTF-8"?>
<amf unit="millimeter">
  <object id="0">
    <mesh>
      <vertices>
        <vertex>
          <coordinates>
            <x>0</x>
            <y>1.32</y>
            <z>3.715</z>
          </coordinates>
        </vertex>
        <vertex>
          <coordinates>
            <x>0</x>
            <y>1.269</y>
            <z>2.45354</z>
          </coordinates>
        </vertex>
        ...
      </vertices>
      <volume>
        <triangle>
          <v1>0</v1>
          <v2>1</v2>
          <v3>3</v3>
        </triangle>
        <triangle>
          <v1>1</v1>
          <v2>0</v2>
          <v3>4</v3>
        </triangle>
        ...
      </volume>
    </mesh>
  </object>
</amf>
```

Figure 29 AMF File

(ISO - ISO/ASTM 52915:2020, Specification for Additive Manufacturing File Format (AMF) Version 1.2)

Similarly, Figure 30 shows the various elements of the AMF file as listed in the ISO/ASTM 52915:2020 standard, including details of various specifications of the product, including material, color, and metadata. Along with that, the standard lists the various attributes associated with each element of AMF. Using this format will enable AIRC to develop an AMF file in XML format that will be consistent with organizations following the same standard.

Element	Parent element(s)	Attributes	Multiple elements allowed?	Description
<amf>		unit version	No	Root XML element. The units to be used may be "inch", "millimetre", "metre", "foot" or "micron". The amf specification version of this file in the format of X.XXX
<object>	<amf>	id	Yes	An object definition. A unique integer identifying this object.
<color>	<material> <object> <volume> <vertex> <triangle>		No	The color to display the object in and to fabricate it in if supported. When conflicting color specifications exist, precedence is given according to the order listed in the specification.
<r>, <g>, , <a>	<color>		No	Red, green, blue and alpha (transparency) component of a color in sRGB space, floating point values ranging from 0 to 1. The values may be specified as constants or as a formula depending on the coordinates.
<mesh>	<object>		No	A 3D triangular mesh definition.
<vertices>	<mesh>		No	The list of vertices to be used in defining triangles in the mesh.
<vertex>	<vertices>		Yes	A vertex to be referenced by triangles.
<coordinates>	<vertex>		No	Specifies the 3D location of this vertex.
<x>, <y>, <z>	<coordinates>		No	x, y, or z coordinate, respectively, of a vertex position in space.
<normal>	<vertex>		No	Specifies the 3D normal of the object surface at this vertex.
<edge>	<vertices>		Yes	Specifies the 3D tangent of an object edge between two vertices.
<dx1>, <dy1>, <dz1>, <dx2>, <dy2>, <dz2>	<edge>		Yes	The normalized x, y or z component (respectively) of the first or second edge direction vector.
<nx>, <ny>, <nz>	<normal>		No	The normalized x, y or z component (respectively) of a surface normal at a vertex.
<volume>	<mesh>	materialid	Yes	Defines a volume from the established vertex list. The id of the material to apply to this volume.
<triangle>	<volume>		Yes	Defines a 3D triangle from three vertices, according to the right-hand rule (counter-clockwise when looking from the outside).
<v1>, <v2>, <v3>	<triangle> <edge>			Index of the vertices defining the triangle or edge.
<texture>			Yes	Specifies texture data to be used by a color or by a tex function in a formula. Contains a sequence of Base64 encoded values specifying values for pixels of a texture.
		id		Assigns a unique texture id for the new texture.
		width		Width (horizontal size, x) of the texture, in pixels.
		height		Height (lateral size, y) of the texture, in pixels.
		depth		Depth (vertical size, z) of the texture, in pixels.

Figure 30 AMF elements from the ISO/ASTM 52915:2020 standard.

(ISO - ISO/ASTM 52915:2020, Specification for Additive Manufacturing File Format (AMF) Version 1.2)

(Figure continued)

Element	Parent element(s)	Attributes	Multiple elements allowed?	Description
<material>	<amf>	id	Yes	An available material for reference by volumes or composites. A unique material ID. Material ID "0" is reserved to denote no material (void) or sacrificial material.
<composite>	<material>	materialid	Yes	Blends existing materials. Value provides a numeric constant or mathematical function of coordinates x, y, z specifying the proportion of material of type materialid. If the value is negative, it shall be treated as zero. The proportions shall be normalized to add up to 1, unless they are all zero, in which case no material is specified (void). A materialid value of "0" shall be treated as a reference to no material (void). The void material shall not be mixed. See A1.2 for a list of allowable mathematical functions. Reference to an existing material. Reference shall not be recursive or cyclic.
<constellation>	<amf>	id	Yes	A grouping of objects or constellations with specific relative locations. The Object ID of the new constellation being defined.
<instance>	<constellation>	objectid	Yes	An instance of an object or constellation to print. A reference to the ID of the existing object or constellation being instantiated. Recursive or cyclic references shall not be used.
<deltax>, <deltay>, <deltaz>	<instance>		No	The distance of translation in the x, y or z direction, respectively, in the referenced object's coordinate system, to create an instance of the object in the current constellation
<rx>, <ry>, <rz>	<instance>		No	The rotation, in degrees, to rotate the referenced object about its x, y and z axes, respectively, to create an instance of the object in the current constellation. Rotations shall be executed in order of x first, then y, then z.
<metadata>	<amf>, <object>, <volume>, <material>, <vertex>	type	Yes	Specify additional optional information about an entity. The type of the attribute. Values shall be one of the following: "name" - The alphanumeric label of the entity may be used by the interpreter when interacting with the user. "description" - A description of the content of the entity. "url" - A link to an external resource relating to the entity. "author" - Specifies the name(s) of the author(s) of the entity. "company" - Specifies the company generating the entity. "producer" - Specifies the name of the originating software and version. "revision" - Specifies the revision of the entity. "tolerance" - Specifies the desired manufacturing tolerance of the entity in entity's unit system. "volume" - Specifies the total volume of the entity, in the entity's unit system, to be used for verification (applies to object elements and volume elements only). "elasticmodulus" - Specifies the elastic modulus of the entity, in SI units (material only). "poissonratio" - Specifies the Poisson Ratio of the material, in SI units (material only). "colorprofile" - The ICC color space used to interpret the three color channels <r>, <g> and .

Figure 30 (continued) AMF elements from the ISO/ASTM 52915:2020 standard
(ISO - ISO/ASTM 52915:2020, Specification for Additive Manufacturing File Format (AMF) Version 1.2)

1.21 ADDITIVE MANUFACTURING DATA PROCESSING OVERVIEW

ISO/ASTM 52950:2021 standard lists the overview of the data processing and process steps involved in the additive manufacturing process. This standard lists the considerations for data exchange in AM data preparation and processing, along with the process flow of AM process. In addition, this standard lists the various file formats (STL, STEP, XML) typically utilized in the AM process steps. Apart from that, this standard lists the potential errors which might arise in the AM manufacturing process along with the mitigation for such errors. Moreover, this standard contains best practices for setting export parameters for: chord height, aspect ratio and resolution; surface tolerance, absolute surface smoothing, absolute; facet deviation, maximum deviation distance, conversion; tolerance, adjacency tolerance. Figure 31 lists the process flow of the AM process from product idea initiation, design generation, to the printing of parts.

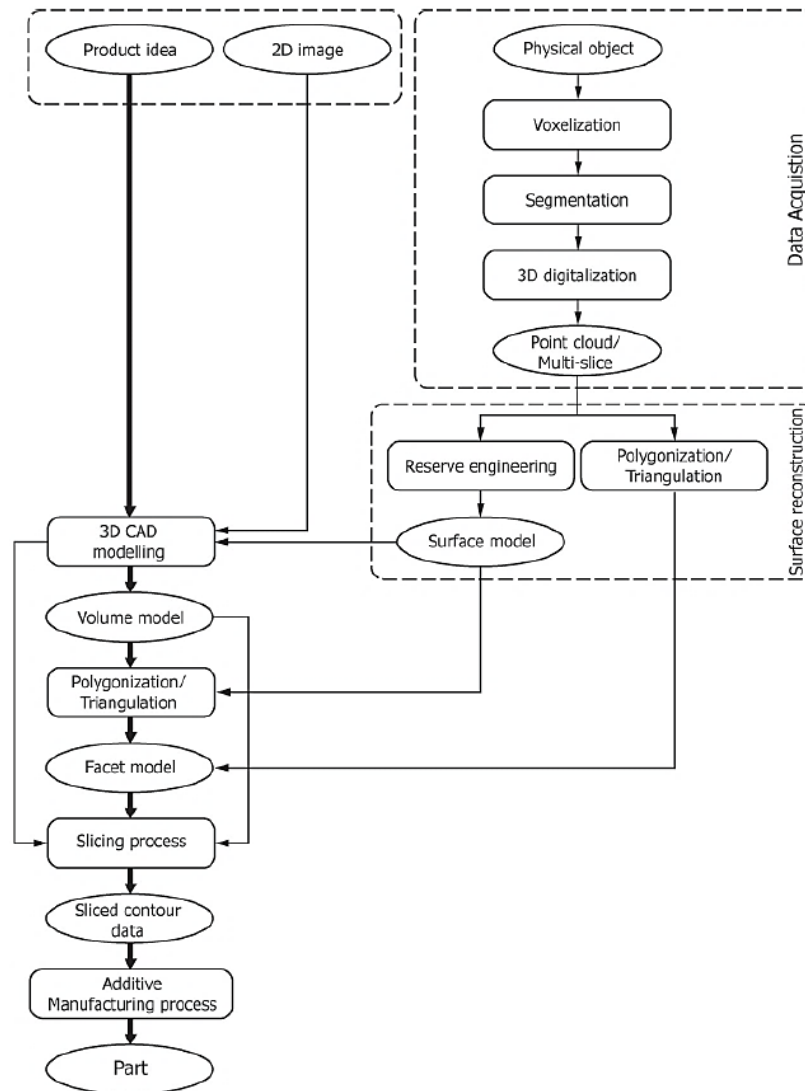


Figure 31 AM process flow.

(ISO - ISO/ASTM 52950:2021, Additive Manufacturing, General Principles, Overview of Data Processing)

1.22 TECHNICAL DATA PACKAGE (TDP) STANDARD

MIL-STD-31000B standard lists the checklist or items that form the Technical Data Package (TDP) for a product. The TDP enables an authoritative source of truth about the product by integrating model-based data in a human-readable and machine-readable form, usually by packaging such data within a PDF wrapper. This arrangement typically results in creating and sharing unambiguous data of the product and supports the design, manufacturing, services, and disposal of products, and since a PDF file is commonly readable by most computing platforms, seamless sharing of information can be had across the lifecycle. Figure 32 shows the list of items that constitute the technical data packages – models, drawings, specifications, standards, software documentation, associated lists, and packaging details (MIL-STD-31000B, 2013)

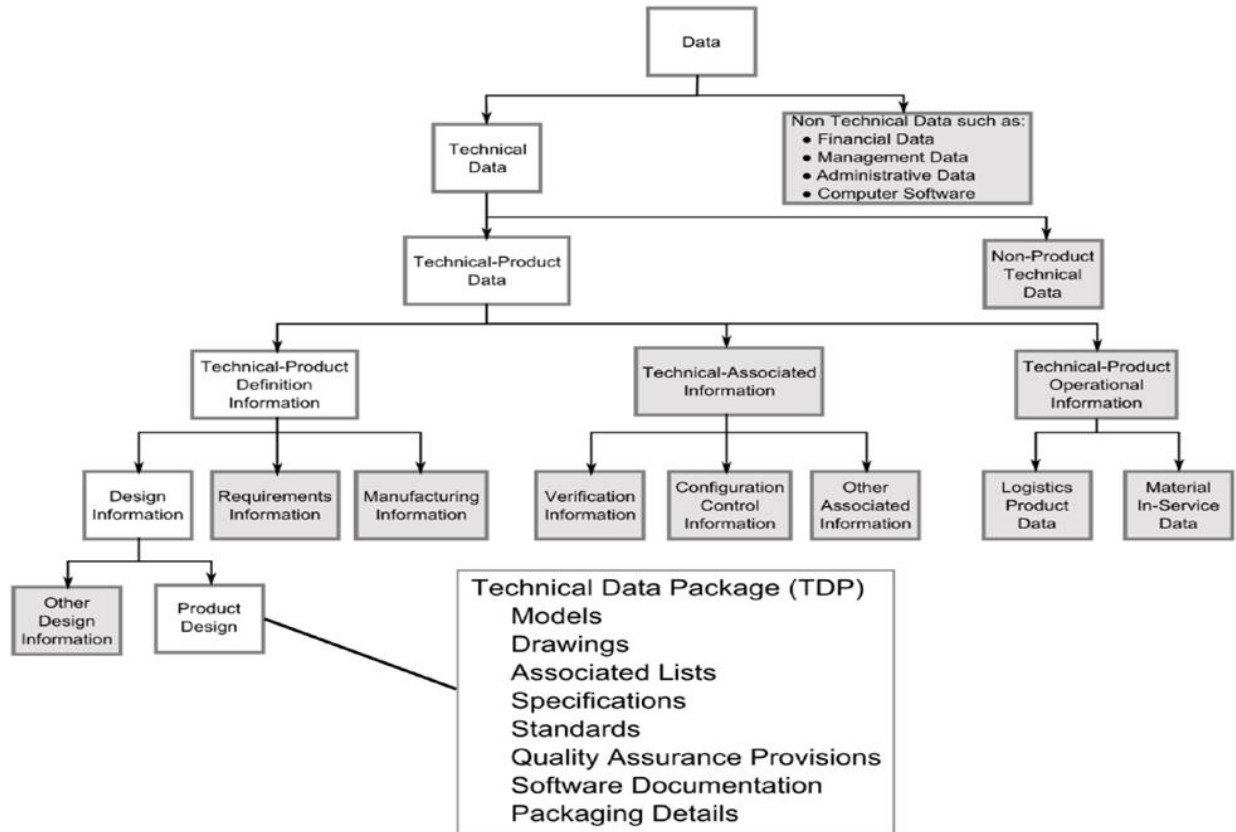


Figure 32 Technical data package.

(Military Standard MIL-STD-31000B, Department of Defense Standard Practice: Technical Data Packages (TDP))

After reviewing the ISO/ASTM 52915:2020, ISO/ASTM 52950:2021, and MIL-STD-31000B standards, it was observed that the data package specific to AM is missing in these documents. Researchers and professionals associated with the National Institute of Standards and Technology (NIST) have published standards for AM data packages which are widely used in academic literature. Those relevant articles were gathered and reviewed to determine which forms of a data package could be specifically used for metal additive manufacturing processes. The next two sections cover the findings from the NIST and academic literature works, which supports the development of the data package necessary for manufacturing products through metal AM practices and sustainment of the AM method for the AIRC use case.

1.23 ACTIVITIES IN AM DIGITAL TWIN ADOPTION

To effectively develop a digital twin of the AM process, one must account for geometry features, materials definition and characteristics, and process parameters. According to Kim et al. (2017), the various activities associated with metal additive manufacturing break down into the following schema:

- Activity 1: generate AM design
- Activity 2: process plan- machine independent

- Activity 3: process plan – machine dependent
- Activity 4: build part
- Activity 5: post-process part
- Activity 6: qualify part

These six activities (noted in the boxes), along with the list of inputs and outputs, are displayed in the form of the flow chart in Figure 33.

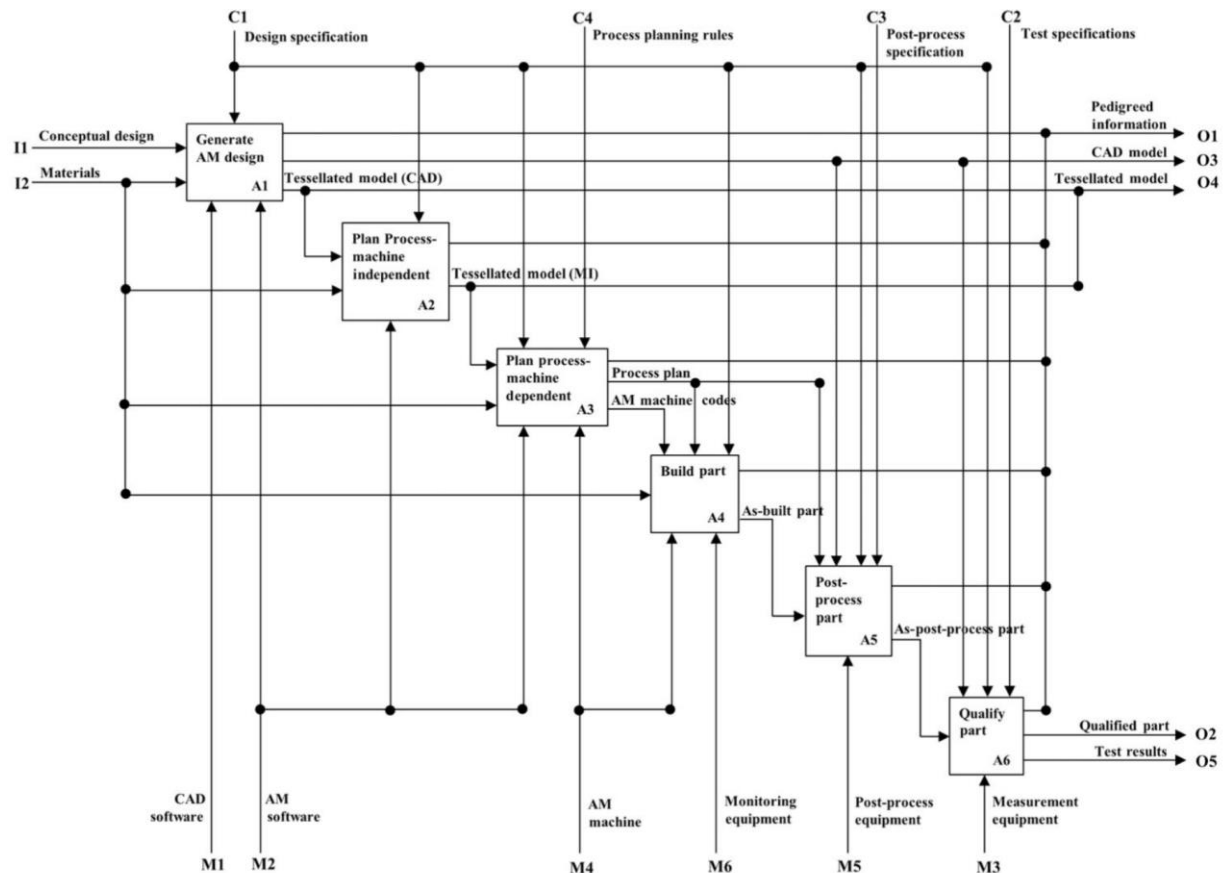


Figure 33 Metal AM activities (A1 to A6).
(Kim, Witherell, Lu, et al.)

1.24 DATA PACKAGE, TOOLS, AND FILE FORMATS.

After reviewing Kim et al. (2015, 2017) and Qin et al. (2019), it was determined that for each Activity, there are certain attributes and sub-attributes that act as the key input for completing the additive manufacturing process. Figure 34 shows the various attributes and sub-attributes of Activities 1 through 3 in the metal additive manufacturing practices. For each Activity, along with these attributes and sub-attributes, Figure 34, Figure 35, and Figure 36 show the various tools and the file format of each Activity.

Activity Attributes	A1- Generate AM Design		A3- Process Plan – machine dependent	
	Create Design 3D Model PMI information Material type Design requirements 3D Tessellated Model 3D Model creation plan Facet type, Surface resolution Machine Specification Build capacity, Accuracy Feature manufacturability	A2- Process Plan – machine independent Part Orientation Orientation angle Support structure (SS) SS Characteristics Contact points btw part, structure, plates SS material, SS type	Slicing Individual layers with XY coordinates Multi-features representation Process parameter determination Process parameter: laser power; scan - speed, pattern, layering strategy Exposure type Process setup plan Machine specifications Powder characteristics Setup plan	
Tools	CATIA NX Creo Adobe Acrobat	Adobe Acrobat Anark AM software	AM software MES, Adobe Acrobat	
File format	Native CAD, prt STEP, STL AMF 3D PDF, PDF	STEP, STL gcode 3D PDF	Native CAD, prt STEP, STL gcode 3D PDF, PDF	

Figure 34 AM activities and attributes for A1 to A3

(Kim, Witherell, Lipman, et al.)

(Kim, Witherell, Lu, et al.)

(Qin et al.)

Activity Attributes	A4- Build Part	
	Preparation – machine setup Initial bed temp. Platform parallelism Laser focal point Build part – process stability Process consistency – laser beam power, chamber pressure & air temp, humidity control, layer thickness, Motion/position accuracy	Powder preparation Powder characteristics: size, morphology, density, chemical composition, thermal properties
Tools	3D printer software Adobe Acrobat ANSYS Dassault System	
File format	STEP, STL 3D PDF, PDF ABAQUS, PATRAN	

Figure 35 AM activities and attributes for A4

(Kim, Witherell, Lipman, et al.)

(Kim, Witherell, Lu, et al.)

(Qin et al.)

A5- Post-Process Activities		A6- Qualify part		
Activity Attributes	Support removal Test methods & plan – CMM & guidelines External dimensional accuracy, external & internal accuracy Thermal Property enhancement Heat treatment method process plan	Surface texture enhancement Method and process plan for surface texture improvement, shot penning plan Accuracy enhancement Process plan for machining/finishing AM part	GD&T test plans Test methods & plan – CMM & guidelines External dimensional accuracy, external & internal accuracy Defects & Microstructure Test plan for cracks & porosity, Test methods and plans for microstructure	Surface roughness Test plan for surface roughness – device, coordinates, testing points, metrics Part properties Test plan for mechanical (ASTM E8), electrical, chemical, and thermal properties
Tools	3D printer software Adobe Acrobat ANSYS Dassault System		PC-DMIS ANSYS (As-Design) Dassault System Adobe Acrobat	
File format	STEP, STL 3D PDF, PDF ABAQUS, PATRAN		STEP, STL 3D PDF, PDF ABAQUS, PATRAN	

Figure 36 AM activities and attributes for A5 to A6

(Kim, Witherell, Lipman, et al.)

(Kim, Witherell, Lu, et al.)

(Qin et al.)

The NIST-AM model suggests that an additive manufacturing digital strategy has three levels of process maturity in the digital spectrum. First, the data package necessary for Activity 1 – generate AM design constitutes the ‘producibility data package,’ which includes the basic information such as GD&T for producing part. The producibility data package and data package of Activities 2 through 4 constitute the ‘repeatability data package.’ This enables the repeatability and verification of the process and includes details such as the process plan and information manufacturing part in AM machine. The repeatability data package, along with data packages of Activity 5 and Activity 6, constitutes the ‘reproducibility data package.’ The reproducibility data package supports the part definition, verification, and also qualification of the process for long-term sustainment of the process. Therefore, attaining the third-level process maturity will result in a qualified process that will be reliable for manufacturing parts by the metal AM method.

The data package necessary for Activity 1 constitutes the **producibility data package**. The contents of the producibility data package and data package of Activities 2, 3, and 4 constitute the **repeatability data package**. The repeatability data package, along with data packages of Activities 5 and 6, constitutes the **reproducibility data package**. Figure 37 shows the data packages that constitute the various levels of the process maturity spectrum.

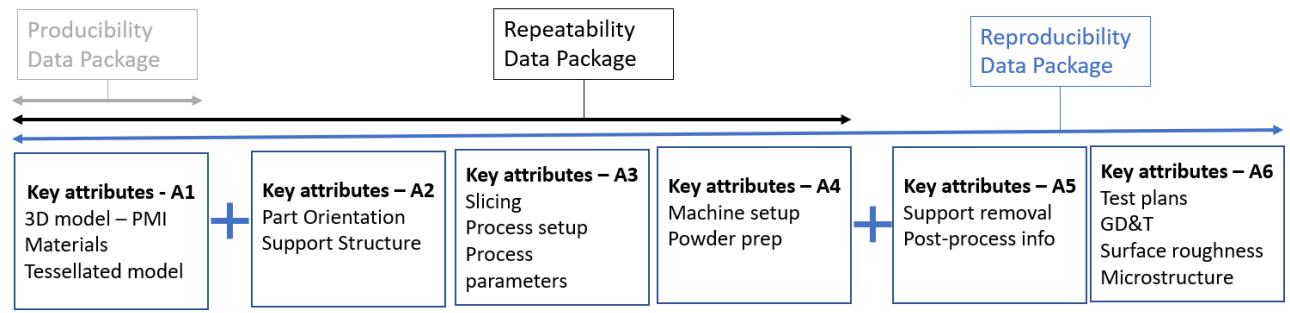


Figure 37 Data packages for metal AM activities

1.25 ROADMAP

Based on the observations from the literature and the findings, a roadmap was developed to guide the sequential adoption of metal additive manufacturing for the AIRC use case. The roadmap contains various steps involved in the adoption of digital engineering strategy for AIRC use case for adoption of AM practices and MBE approach. The roadmap acts as guidance for the transformation team involved in the implementation of digital engineering strategy at DoD. As aforementioned above, the roadmap shown in Figure 38 has been developed to guide the AIRC through step-by-step execution of digital engineering strategy beginning with the creation of a data package of the metal AM process.

The first step in the roadmap is to create the 3D Model Based Definition (MBD) models for the product. Training on the creation of valid MBD data sets; adoption of PDM workflows; and implementation of PLM tools to manage digital definition across the lifecycle (including portals for suppliers) may be necessary. Then, gather all the information and items that constitute the data package for the metal AM activities from Activity 1 through Activity 6. Identifying, selecting, and implementing a robust 3D TDP authoring and dissemination system is critical to the success of the second step. Along with that, the DoD (or the OEM) that is governing the product design should assemble the technical data package of the product. All these data packages support the sustainment of metal AM practices.

Adopting metal AM processes and technologies require not only the creation of MBD (digital) models but also the technological infrastructure both internally and within the supply chain to create, share, and consume the MBD or digital engineering data. Therefore, in order to sustain the adoption and use of metal AM, OEMs should evaluate the readiness of their supply chain and assess the capability of their suppliers to practice digital engineering activities. The useful metric here might include assessing the capability of 3D CAD/CAM usage by personnel across the supply chain; knowledge of AM processes and process optimization for the machines being used; the nature of the AM machines being used regarding build size, precision, build time; knowledge and use of metrology/quality techniques and tools appropriate to AM methods.

After conducting the readiness or maturity assessment, the OEM should identify and close the technological gap among their suppliers that may hinder the usage of digital engineering

approaches in their supply chain, which could include updated contractual requirements, access to training and professional development, cost-sharing business models, or other techniques to mitigate the surge in expenditures needed by the tiered supply chain to address their deficiencies.

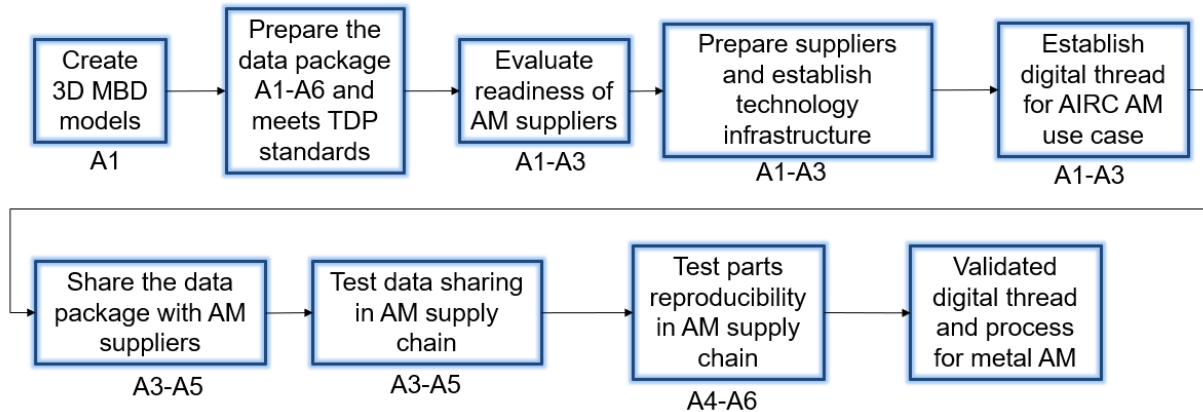


Figure 38 Roadmap for digital engineering strategy implementation

Once this step is complete, the OEM should establish the digital thread for sharing the product data and manufacturing parts via AM method. This step should include information about software systems used; data types and formats needed and provided under the terms of the supplier contract; data types and formats needed to share product and process information across the lifecycle (specifically, the MBD object information); any validation and verification data needed to check against the digital artifact; and potentially any hardware, software, and network information needed to support interoperability and cybersecurity. Along with establishing the digital thread, the DoD should work with their OEM contractor to test these data-sharing practices for instituting effective data management and sharing practices.

Once the data sharing practices have been established, the DoD has to support suppliers' capability to produce parts that meet the specification and build reproducibility of the process, such as addressing contracting requirements to reflect digital methods and tools or develop digital engineering expertise within the various program offices and officer ranks within the materiel commands. Reproducibility is necessary for proving the process capability of the metal AM process and establishing it as an alternative option for traditional subtractive manufacturing. Completing all these steps in the roadmap can provide a validated digital thread and validated process protocols for AM process, which the DoD can sustain for the AIRC acquisition use case.

1.26 SUMMARY/FUTURE WORK

Additive manufacturing provides an alternative approach for manufacturing products across the supply chain. Some of the benefits of using AM are inventory reduction in the supply chain yet increasing supply chain resilience through alternate options; quicker response to surge demands and warfighter readiness; and manufacturing products with complex design (Qin et al., 2019)

while actively reducing the number of serviceable components. This report aimed to review the recommendations and requirements proposed by the DoD for metal AM adoption and to develop guidance for AIRC's use case. This review originated a sample roadmap and a suggested data package framework for metal AM methods and tools, which supports the AIRC in developing data packages necessary to support the adoption and continued use of metal AM techniques within the DoD acquisition functions. These recommendations have been developed based on the review of standards, literature, and DoD recommendations. The results of this report can (and should) be validated and refined by conducting case studies of AM implementation through the suggested roadmap and data packages.

Conclusions

Subtask WRT-1049.4 focused on the data and framework surrounding the opportunity to exploit additive manufacturing as a systems engineering problem. First, we identified the critical decision and analysis variables and created a framework to understand how these variables impact each other. Second, we transferred the above framework into an algorithmic view of these variables to make an optimized decision regarding where and how additive manufacturing can have the most impact. Third, we developed an interactive decision support tool (i.e., "Decision Engine") in additive manufacturing, supply chain, and digital engineering as part of the overarching goal of mission engineering.

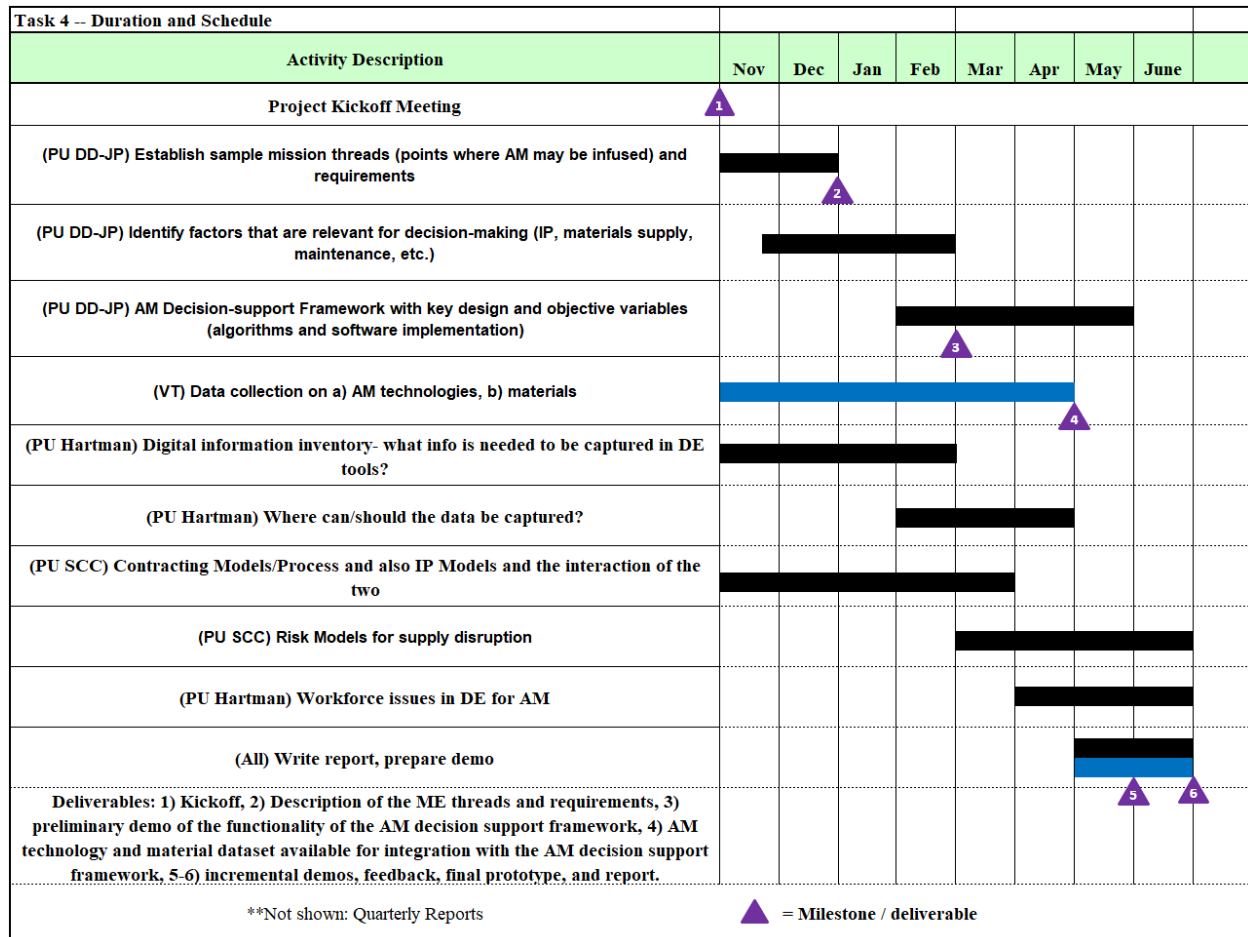
This report started with a description and conceptual background on the decision support tool. Then, we discussed three use cases that we analyzed to create the Decision Engine: 1) Aircraft Fleet Maintenance using Additive Management, 2) Spacecraft Applications, and 3) Design, Manufacturing, and Maintenance of Aircraft Components. Finally, the report concluded with the presentation of a roadmap for creating digital technical data packages for the adoption of additive manufacturing.

Further possibilities of the Decision Engine development include 1) driving the decision engine using Model-based Systems Engineering (MBSE); 2) Integration of the decision engine with System-of-Systems (SoS) Analytic Workbench (AWB) for Mission Engineering; 3) Integration of the decision engine with AM machine/material databases (e.g., Senvol, PW Communications); 4) Integration of the decision engine with generative design tools to explore part redesign opportunities (and associated savings) via the use of AM (e.g., Autodesk Fusion 360); and 5) Expansion of Decision Engine to other DoD's area of interest, such as crisis management as discussed during the Additive Manufacturing Workshop in June 2022 at the MxD Headquarters in Chicago, IL (*2022 Additive Manufacturing Workshop*).

Project Timeline & Transition Plan

Original Research Contract Performance Period

The research contract had the period of performance ending at the end of June 2022. To this end, Figure 39 depicts the project timeline for the original research contract.



Legend:


Purdue
VT

Figure 39 Project timeline for the original contract

Contract Extension Performance Period

In addition to the original contract described above, we received an extension to the original contract period. The research extension allowed us to conduct research through the end of September 2022. Thus, we created a separate project timeline for the contract extension (Table 13).

Table 13 Project timeline for the contract extension

Milestone	Completion Date
Software Development and Database - Integrate a relevant decision from Use-Case 1 with the software engine - Integrate Use-Case 3 with the Decision Engine - Revamp the user experience with more useful information for the decision maker	7/31/2022 8/31/2022 8/31/2022
Use Case 1: Aircraft fleet maintenance - Determine how the mixed priority mission affects optimization (Impact of priority) - Integrate aircraft fleet maintenance as a part of the decision support tool - Determine how AM affects the optimization process	8/31/2022 9/15/2022 9/15/2022
Use Case 2: Spacecraft applications - Finalize relevant mission- and component-level requirements diagram for the satellite use case - Enhance the existing attributes (i.e., performance, cost, time) as a part of the input for the Decision Engine	7/31/2022 8/31/2022
Use Case 3: Single component design and manufacturing - Integrate the SysML model with the decision support tool - Provide assistance in accessing and utilizing AM database (Virginia Tech) - Continue collaboration with Purdue researchers to share knowledge on AM process and material selection (Virginia Tech)	8/31/2022 8/31/2022 9/30/2022
Digital Engineering Strategy Investigate management, budgeting, and other non-technical models	9/15/2022
Overall - Deliver the initial draft of the final project report - Deliver the final framework decision-support tool software and report	9/01/2022 9/30/2022

Transition Plan

We participated in the AM Workshop in Chicago, IL, on June 28-29, 2022, where we provided our feedback on AM use in crisis management. Also, We presented the research results and demonstrated the prototype Decision Engine to the sponsor on September 20, 2022. As of September 30, 2022, we are investigating the possibility of further research for the Decision Engine improvement ideas shown at the end of the Conclusions section. We are currently working with the AIRC leadership team to identify potential opportunities within DoD. We are hoping that these activities will pave the way for the next phase of the research.

Appendix A: List of Publications Resulted

Shi, Q., Tsutsui, W., Bekdache, D., Panchal, J.H., and DeLaurentis, D. (2022). A System-of-Systems (SoS) Perspective on Additive Manufacturing Decisions for Space Applications. *2022 System of Systems Conference*. Rochester, NY. <https://doi.org/10.1109/SOSE55472.2022.9812665>

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