The Pennsylvania State University

The Graduate School

DFAM+

THE FUTURE DESIGN FOR ADDITIVE MANUFACTURING

FRAMEWORKS AND DESIGN GUIDES

A Thesis in

Additive Manufacturing Design

by

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ABSTRACT

This work is motivated by the discrepancies often found in the promises of Additive Manufacturing's (AM) "Complexity is free" marketing slogans - and the realities of design, manufacturing, certification and the business of solving problems with AM. While it is true that unparalleled complexity is afforded to designers, traditionally limited by subtractive processes, this does not mean that every problem can or should be solved with AM alone. The cost of complexity is dependent on i) the methods used to generate it (Design), ii) the requirements which drove it, and iii) all the manufacturing processes used to achieve the vision of the prior two. The focus on purely the AM process has led to the many of the design frameworks and design guides from the literature being focused purely on printability or the novelty of the processes. The majority of the Design for Additive Manufacturing (DfAM) frameworks posed by the research community are highly iterative in nature, and are scoped to dealing with the just the nuances of the AM processes. The guides published by many machine OEMs and thought leaders in this industry are often explicitly scoped just with the AM process in mind and do not give much ground to the often-necessary post-AM processes used to achieve functional requirements such as surface finish or fitment. The strategies employed to generate the net-shape with additive manufacturing have an effect on the ease or success of those post processes. A new scope of the definition of DfAM is proposed to include deference for secondary manufacturing processes along with the prototype of a new design framework to highlight the multi-disciplinary nature of DfAM projects under this expanded scope and the reality that design and manufacture does not exist in a vacuum. A feature-specific style of design guide is proposed for metal parts produced with laser-based powder bed fusion of metals (PBF-LB/M) to include possible secondary manufacturing processes, as a tool to aid new designers and experienced practitioners in concept development and design decision making. The framework and feature specific guides are demonstrated in the redesign of an F-18 engine subsystem component.

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To thank my family for their patience and encouragement over the years. Especially my Mimi and Papa, without fail you always gave encouragement.

Prior to my time at Penn State there were several colleagues seminal to the path I have taken and the engineer I have become. Dr. Amy M. Elliot – in 2012, first introduced me to Additive Manufacturing through the DREAM Vendor at Virginia Tech. Credit to Amy for tricking me into this outstanding field, though apparently I didn’t take much convincing. For challenging me to question the nature of the physics and process mechanics underpinning restrictive DfAM and for the three wonderful years I spent in the Lab - I must thank Dr. Williams for cultivating my curiosity and providing a place to learn lessons beyond the classroom.

From my time with NAVAIR I have too many colleges to thank. Mark Sapp, Douglas Greenwood, and Nicolas Pettaway warrant special mention for the profound influence they have had in shaping my career as an engineer and encouraging me to return to graduate school.

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Chapter 1

Introduction

1.1 Motivation

Additive Manufacturing (AM) has begun it's ascent along the slope of enlightenment to the plateau of productivity [1]. This is evidenced by the fact that larger companies such as GE has stood up an AM consulting organization AddWorks™[2], and an AM division[3], and is producing commercially viable products such as the LEAP Nozzle[4]. Additional evidence is given by NAVAIR's efforts to prototype and certify a nacelle linkage produced with PBF-LB/M [5], and to demonstrate the hydraulic manifold [6] shown in Figure **1-1**.

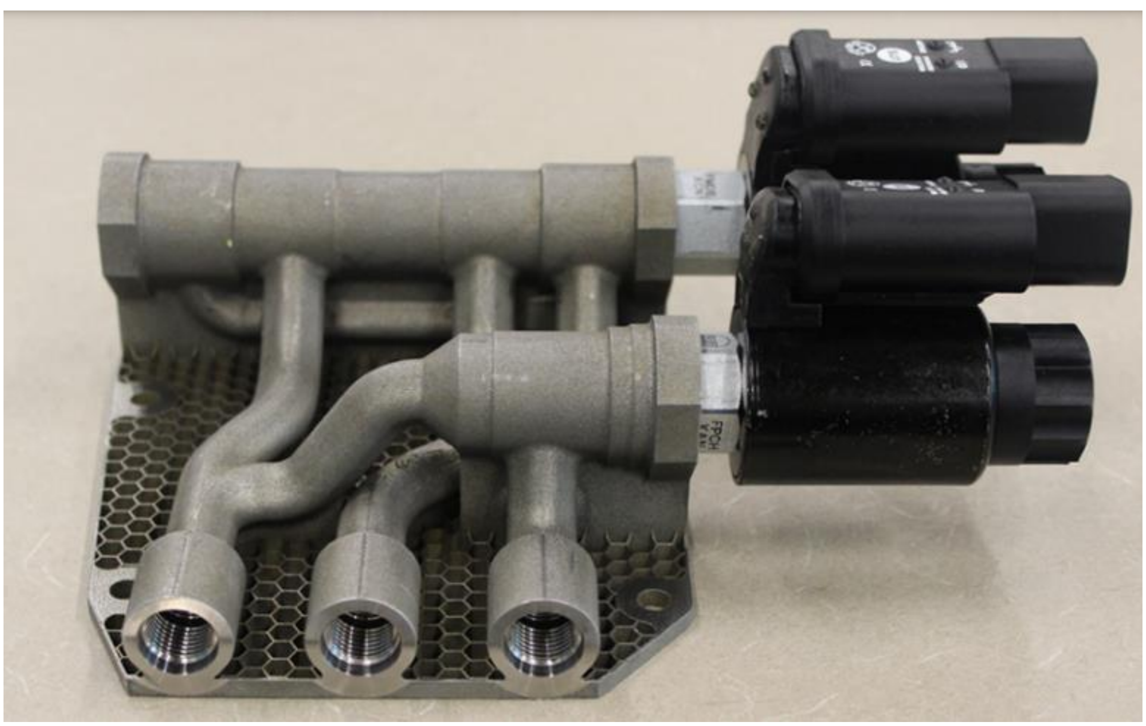


Figure **1-1**: Hydraulic Manifold produced with PBF-LB/M, photo curtesy of CIMP-3D[6]

However, AM as an industry has marketed itself as a proverbial easy button for low volume, high complexity components. With such claims as:

- “Manufacturing complexity is free” [7]
- “Zero lead time” [7]
- “Do not think about tooling because they are no longer needed” [8], [9]

The uninitiated may think that a 3D printer is the last or only manufacturing process they would need to acquire to solve all their problems. Many new users of this technology think that parts come out of the AM system ready for end use because these systems are peddled with promises such as “no need for tooling”. These would-be users would quickly discover that the AM process is a single step in a larger Manufacturing Process Plan (MPP) to achieve the requirements necessary to have a finished product.

1.2 Scope

The Center for Innovative Material Processing through Direct Digital Deposition (CIMP-3D), was created explore the capabilities of and craft the future for AM technology, to include research into the areas of DfAM for Powder Bed Fusion with a Laser Beam on Metal (PBF-LB/M). To this end, CIMP-3D engages in research utilizing multiple PBF-LB/M systems, including the EOS M 280 and the 3D Systems ProX 320 and ProX 200 [10], and has developed insights into the nuances of common DfAM principles between these different PBF-LB/M systems. The framework developed herein provides an outline for how a multi-disciplinary team can efficiently take into consideration DfAM principles while also considering the impact on downstream processes along with the cost of design activities. Design guides that address DfAM for PBF-LB/M *coupled with subtractive processes and other finishing techniques* are proposed, along with rules for incorporating supplementary strategies developed at a later time. The aforementioned guides are demonstrated as applied through a case study where the decision making and design processes were documented extensively.

1.3 Objectives

Typically, design efforts are rarely performed by a sole engineer. This for practical reasons as is it rare that a single engineer is gifted with sufficient technical depth or breadth to quickly and effectively bring a complex part to production and use. Often an engineer specializing in manufacturing will work in conjunction with subject matter experts and various other stakeholders to bring a product to market. While AM technologies are often marketed as an “easy button” for bringing complex components to market, in practice they inevitably require subtractive or other post-AM manufacturing processes to satisfy functional requirements. Existing frameworks and guides rarely touch on concerns beyond printability. Implementers are left to develop strategies that leverage DfAM with other manufacturing processes with little guidance, which has slowed the deployment of PBF-LB/M in the DoD and other industries. This work aims to expand the definition of DfAM to include considerations for other processes and to provide a roadmap for how this body of knowledge can be expanded upon in the future. Specifically, this work serves to:

- Define DfAM+
- Prototype a framework for DfAM+ of a complex system considering
    - The coupled effects of AM design decisions on secondary processes
    - The impact of design decisions on cost, schedule, and final part qualification
    - Methods to communicate DfAM concerns as a member of a multi-disciplinary team

    - Strategies to reduce the risk of expensive design changes
- Create a DfAM+ guide

1.4 Organization of Thesis

To achieve these aims, this thesis presents works relevant to many of the misconceptions around DfAM and past efforts to consider other manufacturing processes in Chapter 2. Specifically it looks at the underlying research which propagated the notion of “complexity is free” and where those studies break down. Frameworks which are used as tools to teach design thinking about this technology from an academic perspective can be rather costly if applied verbatim in industry, these limitations are highlighted to show shortfalls in some previous academic efforts. Chapter 3, defines DfAM+ and provides the reasoning behind the creation of a framework applicable to industry. Chapter 4, demonstrates the applicability of the DfAM+ framework by applying it to the redesign of a Pressure Bleed Air Regulator (PBAR) for PBF-LB/M. The latter portions of Chapter 4 provide insights and lessons learned from the case study as well as outline opportunities for future work. Chapter 5 summarizes the findings and concludes the thesis.

Chapter 2

Literature Review

2.1 Introduction

Literature pertaining to a number of the misconceptions surrounding DfAM are first explored to establish the need for primary and secondary machining. Design frameworks which provide opportunity for incorporating considerations for primary and secondary machining are evaluated to show what a number of them did well and where they can be improved upon. This analysis formed the rationale underpinning the DfAM+ framework.

2.2. The True Cost of Complexity in Additive Manufacturing

The year 2013 marked much of the hype surrounding AM, coinciding with Hod Lipson releasing a book entitled “Fabricated, The New World of 3D Printing”. In Lipson’s book the phrase *“Manufacturing complexity is free”* [7] first surfaced and was subsequently used or eluded to in many TED talks[11], [12] as a means to explain much of the excitement around these technologies to the layperson. When people are first introduced to these technologies, many are shown an abstracted graph comparing AM technologies to the cost per part of other manufacturing technologies as shown in Figure **2-1**, in order to define where additive manufacturing is applicable.

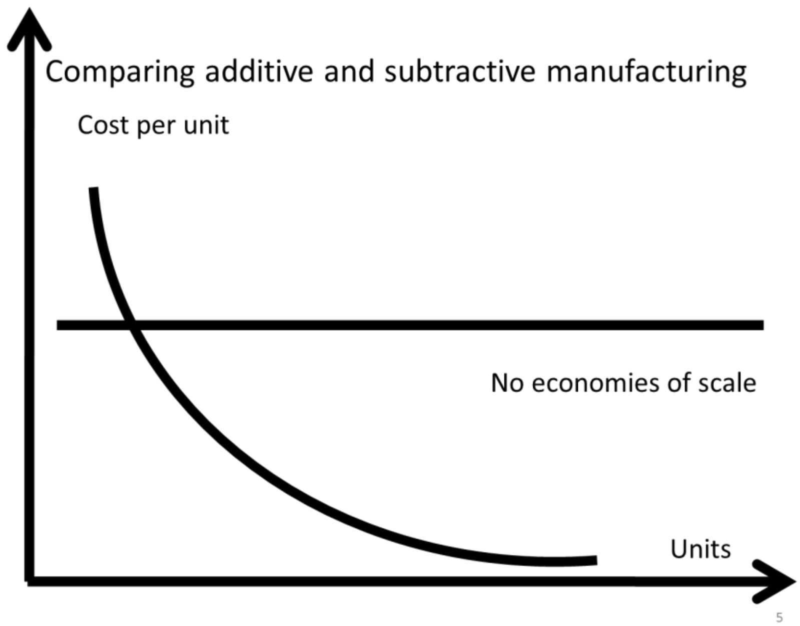


Figure **2-1**: Trend curve comparing AM to Subtractive Manufacturing [13]

Rarely in the underlying research that informs this widely accepted trend cited in presentations. Much of the work that informs this opinion stems from a research group out of Turin Italy[14-16]. They produced a number of case studies where an existing component and its primary manufacturing process were compared to fabrication of the same geometry produced with an AM process, and the cost per part was mapped to see what the cost curve looked like to assess the economies of scale for which it could be considered a viable alternative. The first of such studies occurred in 2010, comparing Injection Molding (IM) to laser-based powder bed fusion of polymers (PBF-LB/P), previously SLS, for a nylon component [14]. Minimal redesign occurred and the authors showcased nesting of components to reduce the cost per part for two sizes of PBF-LB/P systems available at the time. Using quotes for the IM process and quotes for producing the PBP-LB/P process they built a cost comparison shown Figure **2-2**.

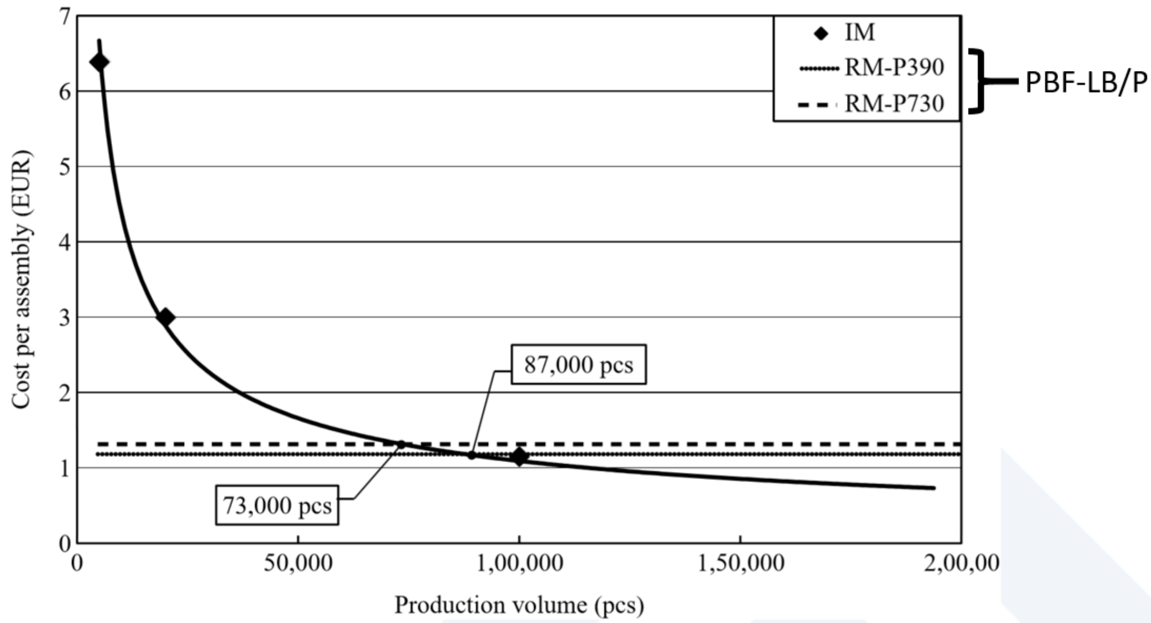


Figure **2-2**: Economies of scale PBF-LB/P compared to Injection Molding (IM) [14].

This same group performed a similar study on a metal landing gear assembly for a general aviation aircraft in 2012[15] and a follow-on to the same study in 2014 [16]. The group leveraged topological optimization to inform a redesign of components of the landing gear assembly. The geometry produced was restricted so that it could be produced with multiple manufacturing technologies, shown in Figure **2-3.**

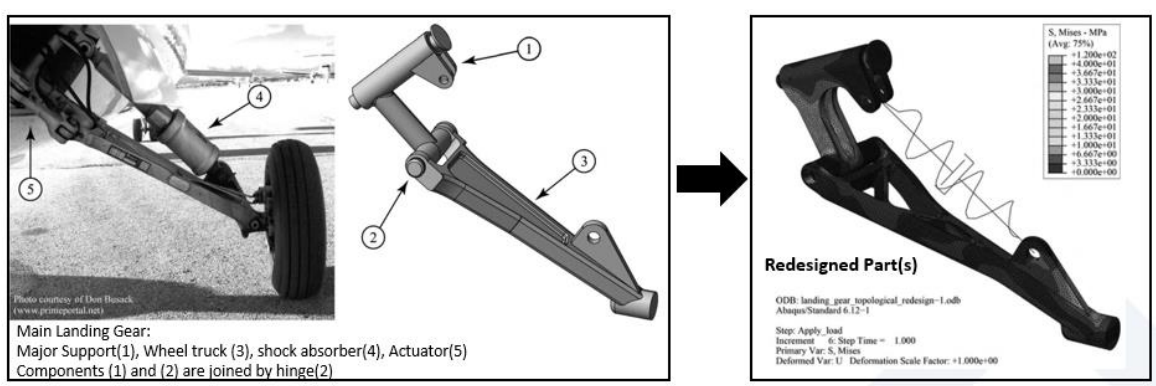


Figure **2-3**: Landing Gear redesigned for High Pressure Die Casting, 5-Axis Machining, and PBF-LB/M to study the economies of scale [15].

In the 2012 study, cost of High Pressure Metal Die Casting (HPDC) was compared to PBF-LB/M, referred to at the time as SLM, in the same manner used for the 2010 study [14]. In the 2014 follow-up [16], 5-axis machining of a billet of comparable material was investigated as a manufacturing technique, and there were minor updates to how cost per part was calculated. This resulted in the cost per part curve shown in Figure **2-4.**

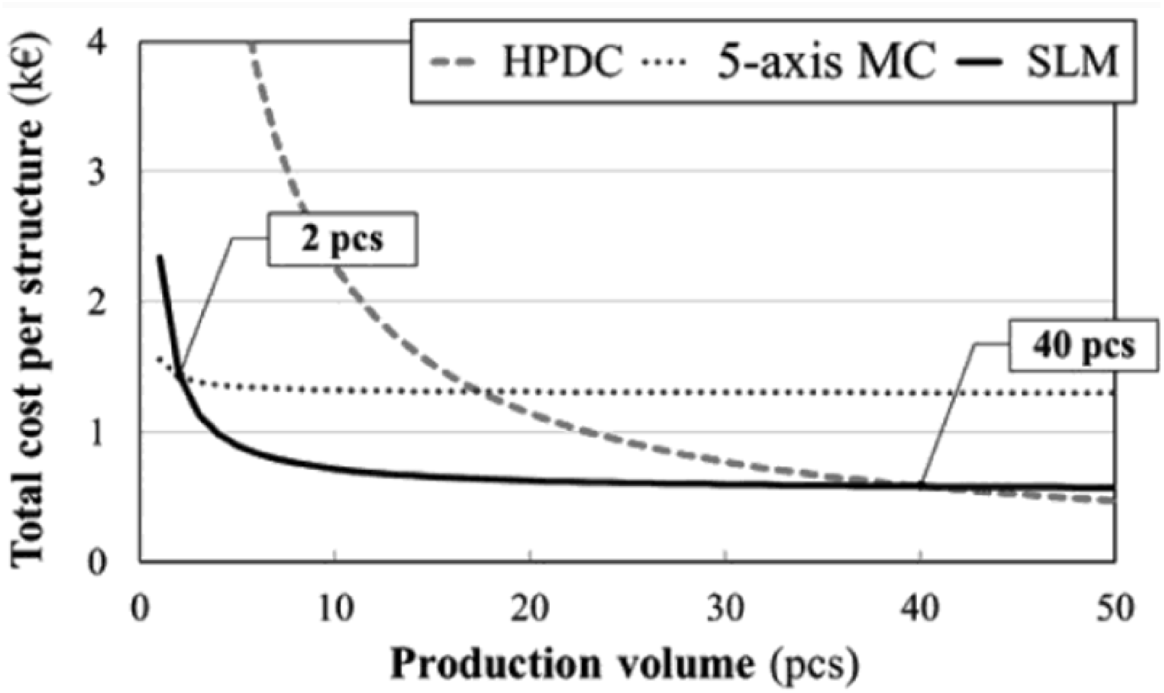


Figure **2-4**: Economies of scale analysis comparing High Pressure Die Casting (HPDC), 5-Axis Machining, and PBF-LB/M (SLM) [16].

While this analysis proved useful for comparing PBF-LB/M to two other manufacturing processes for the same geometry, there are other factors that must be considered. When weighing decisions such as intended manufacturing process, cost certainly plays a factor, but it is typically weighed against performance. At no point in these studies was the life expectancy of the material produced with these various methods weighed against the cost of procurement. HPDC typically has some draft angle applied to the walls so it is removable from the production die, and this same geometry would typically drive up the cost for production with subtractive machining from a billet as the toolpath would be more complex and could require more time. By keeping the geometry consistent between all three technologies, the authors didn't take advantages of the nuances of the different processes or make appropriate design changes to accommodate the differences in material properties, i.e. if HPDC is expected to produce lesser material properties compared to machined billet then the wall thicknesses should have been adjusted accordingly. Aircraft parts, specifically, have many more factors to consider when adjusting the material or manufacturing method, as outlined in the FAA Advisory Circular on Material Substitution [17].

In both of these case studies maintaining the geometry or ignoring the small differences made for the change in process made their analysis possible by arguing the cost of developing the design was the same, allowed them to factor it out of the analysis. This works when the geometry is simple and producible with all methods, but often the change in process necessitates a substantial change in geometry. To take advantage of PBF-LB/M it may be necessary to adjust the geometry. The cost of PBF-LB/M is strongly linked to build height and less so on the complexity of the layer [18], but this only considers the cost of AM and not the knowledge work of design or the cost of subsequent post processing. If these other factors were properly considered by truly redesigning the part for the respective manufacturing techniques, a more comprehensive narrative would have developed and a more robust discussion regarding the applicability of PBF-LB/M for low volume production in this and other applications would have been possible. Given that the design was not manufactured via any of the three methods and the analysis was fraught with gross assumptions based on quotes from manufacturing service bureaus, this work is more theoretical then it should be for the claims it makes.

2.3. Additive with No Need for Subtractive

AM is often considered an easy solution for generating complex shapes without tooling. This has caused many to presume there is no need for tooling or other secondary manufacturing techniques with these processes. For example, in 2010, a group explicitly claimed *"no tooling is needed significantly reducing production ramp up time and expense"* [19]. This claim was later explicitly cited in 2014 [20], and supported by another review paper in 2015 [9]. While there could be an application where the tolerances and surface finish producible with a PBF-LB/M system are acceptable "as-produced", this unlikely to hold true in most practical situations. A review paper in 2016 suggested that processing capabilities, such as nominal tolerances producible with various manufacturing methods, could be used to select an appropriate manufacturing technology [21]. In this work, a table of tolerances for traditional manufacturing techniques and various AM technologies generated by the authors was released for public consumption. In this table, expected dimensional tolerances for PBF-LB/M were shown to not overlap completely with conventional machining or other subtractive processes. This adds credence to the notion that AM, in particular PBF-LB/M, should *only* be considered as a highly capable near-net shape manufacturing process, and implies that this process must be leveraged with conventional machining technologies to satisfy manufacturing requirements AM cannot satisfy effectively on its own. In particular, tight tolerance interfaces or regions where the surface finish produced with PBF-LB/M is unsatisfactory for an application, must be subjected to secondary processes.

Further credence is added to this notion when one considers the GE Bracket Challenge [22]. This work was heralded as an excellent example of DfAM for PBF-LB/M. One could argue that the competition was incomplete as the participants only needed to provide the optimized

CAD model and GE would take care of machining the interfaces. See Figure **2-5**, for winning design.

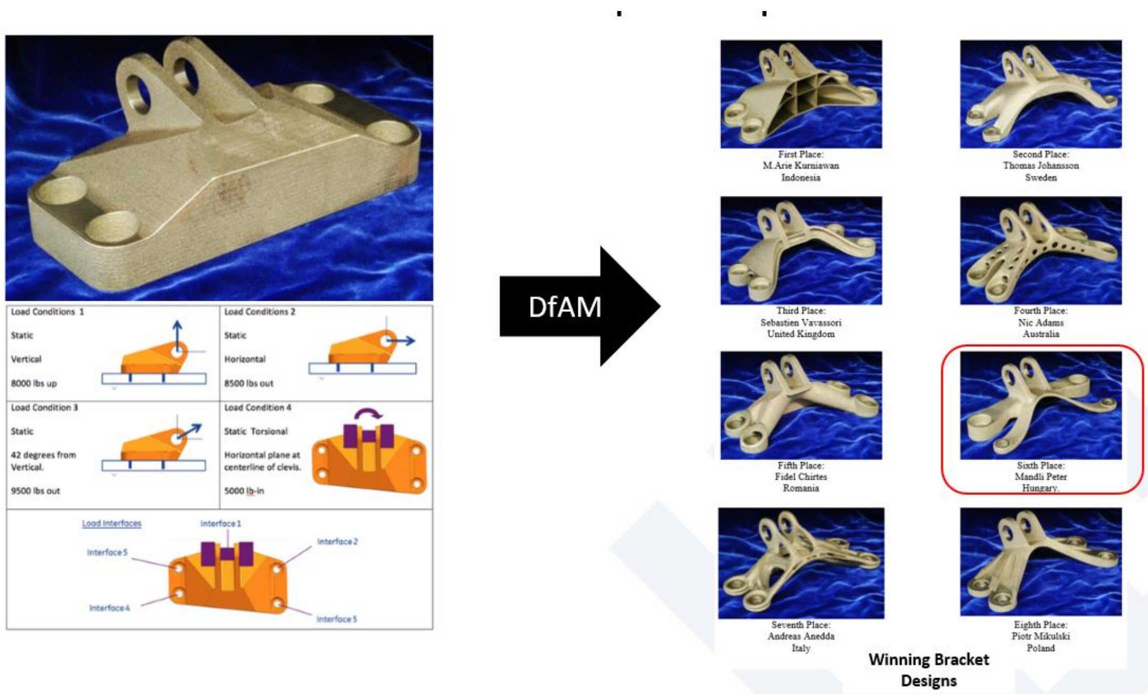


Figure **2-5**: The GE Bracket Challenge, Competition shown Left, Collection of winning designs shown Right with subject of a follow on study circled in Red [22].

GE would later commission a study with DeMeter et.al to modify the design and satisfy the final part requirements. This group ended up drafting the entire down skin surface to the build plate with solid support material, then used Photo Activated Adhesive Workholding (PAAW) fixture to enable subtractive machining to produce a finished part in two manufacturing operations, as shown in Figure **2-6**. This case study demonstrated a need for conventional machining and tooling on an AM part, as well as demonstrated that DfAM decisions pertinent to the As-Built state of the part have a sizable impact on success, failure, and cost of secondary manufacturing processes.

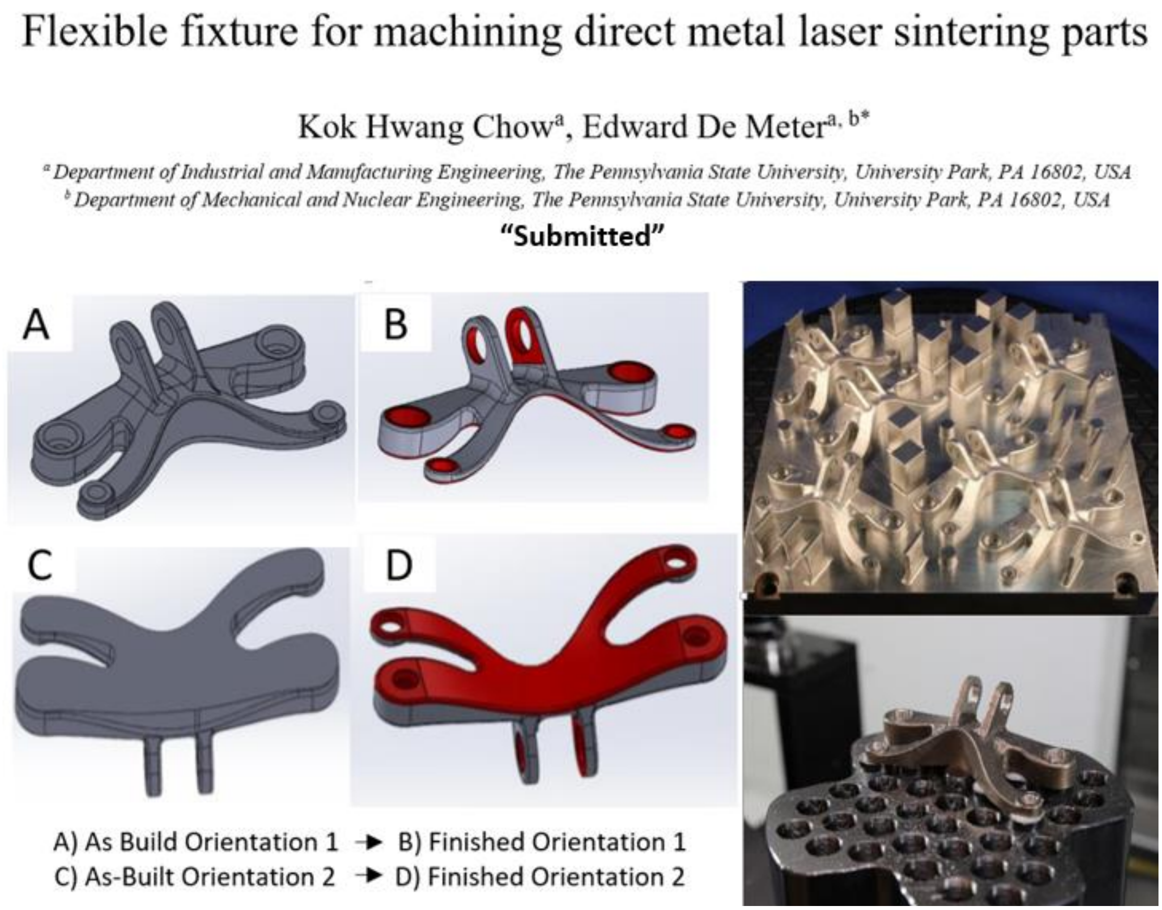


Figure **2-6**: The subject part altered to accommodate the requirements of post processing

2.4. Existing Design Frameworks and Guides for AM

A short survey of a collection of design guides openly available on the internet shows they are concerned more with printability and setting expectations for the process[23]–[25], rather than discussing the nuances of DfAM decisions coupled with conventional machining considerations. If they do touch on machining considerations the guidelines are more advice for adding machining stock on the order of 0.5–1 mm or under sizing fastener holes to be drilled to final size later. None of the guides touched on indexing or locating the component for machining; the concept of trading some design complexity for ease of machining appears to be a foreign one.

Design frameworks are often used to initiate new design engineers in how to systematically consider DfAM capabilities and limitations. They are often created by academics in the wake of a case study or are used to showcase a design process flow for leveraging a novel design tool such as topological optimization. Few of these design frameworks hint at the need for giving some deference to subsequent or secondary post processes.

Ian Gibson, David Rosen, and Brent Stucker in the later parts of their textbook "Additive Manufacturing Technologies – Rapid Prototyping to Direct Digital Manufacturing" [26] showcased an idealized DfAM system framework which could be applied to a variety of problem templates. It suggests that the designer implicitly model any solution to be run by a manufacturing planner and subsequent manufacturing simulation where the results can be later analyzed to see if they meet the requirements. Opportunities to insert feedback on the DfAM solution can occur at the Manufacturing Planning or Manufacturing Simulation stage. The process, illustrated in Figure **2-7**, is expected to be highly iterative, enabling a concept to be worked out implicitly and analyzed before the next one is considered.

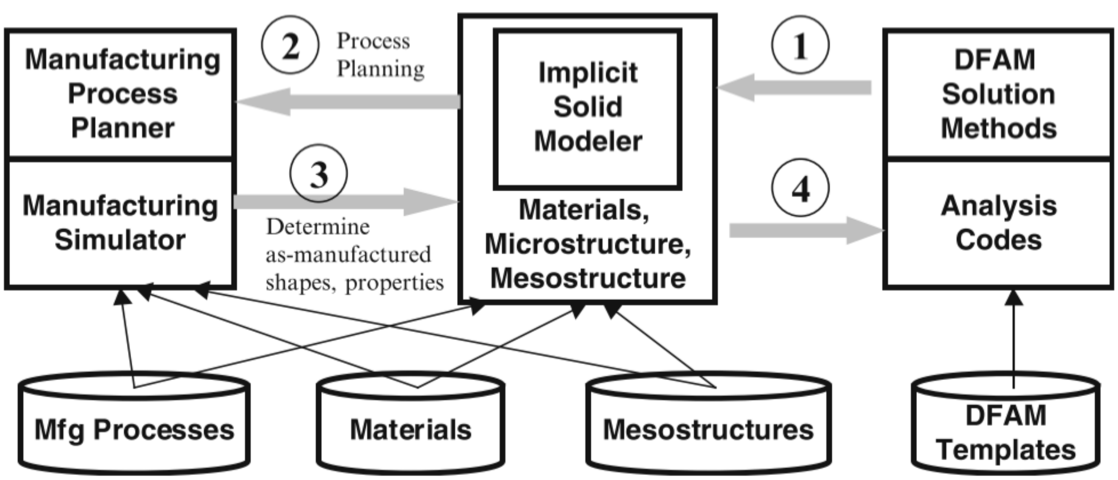


Figure **2-7**: An overarching DfAM framework Gibson et.al. [26]

In 2015, the work "(Re)Designing for Part Consolidation: Understanding the challenges of Metal Additive Manufacturing" [6] was published and elevated the discourse surrounding DfAM with some deference for post processing needs. Particularly note-worthy was the illustration of product definition for both the As-Built and the Post-Machining design, see Figure **2-8**, in a manner similar to the product definition requirements for parts machined from either castings or forgings. Features were added explicitly as manufacturing aids; targets for machining and tapping as well as flats for a wrench to aid in assembly.

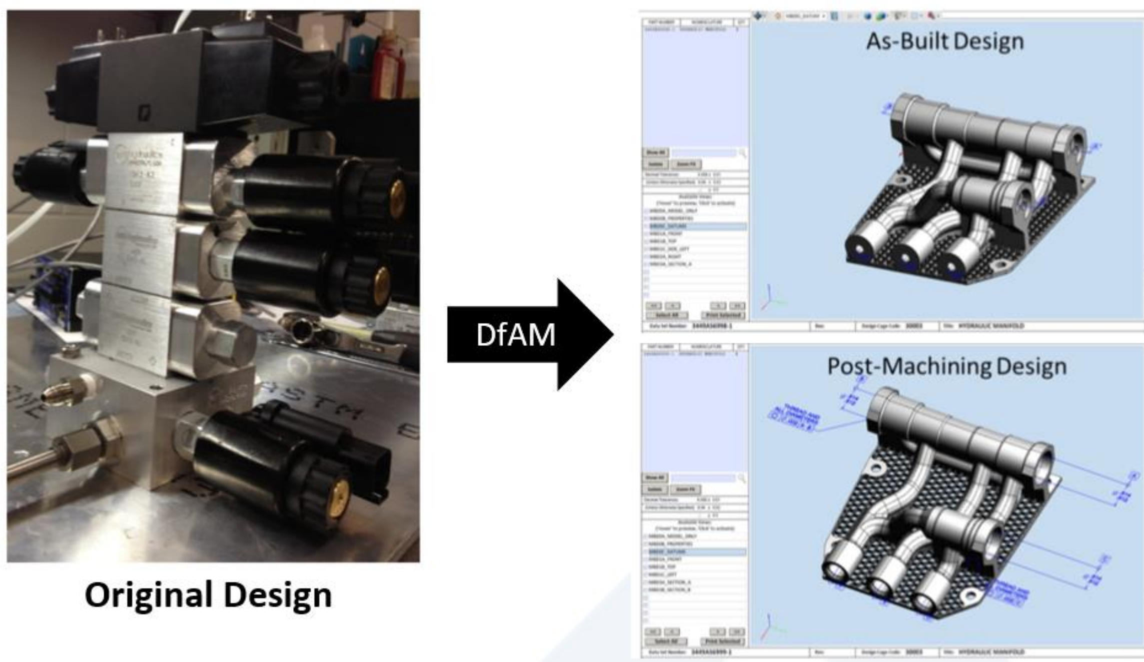


Figure **2-8**: Picture of the original to final part with the two product definitions shown right. [6]

An excellent trade study was conducted on the shape of the complex fluid passages to reinforce the decision of using diamond shaped fluid passages, see Figure **2-9**. The configuration and build orientation studies illustrated how concepts were evaluated using a more-and-more simplified versions of the fluid passage paths until the concepts started to converge, see Figure **2-9**.

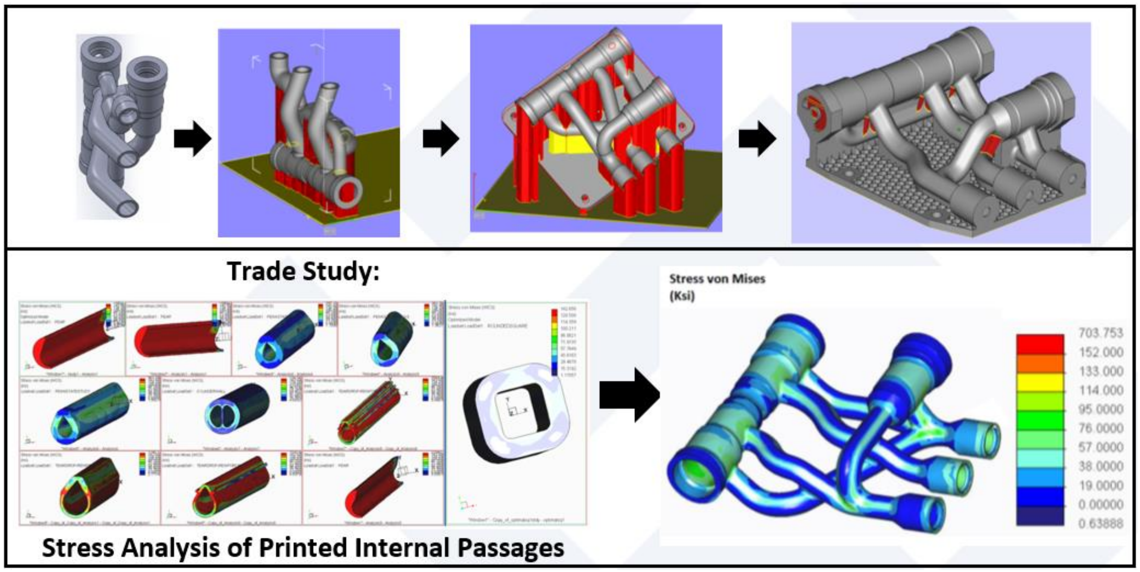


Figure **2-9**: Concept exploration for configuration and build orientation shown Top, Trade study on passage geometry shown bottom. [6]

The illustrated design framework was more robust with smaller feedback loop paths to allow for swift adjustment to the design concepts as the need presents itself. This work concludes with an explicit functional block diagram that outlines how to identify and address post processing needs, along with feedback loops to pertinent nodes where relevant DfAM changes could be made. This diagram is shown in Figure **2-10**.

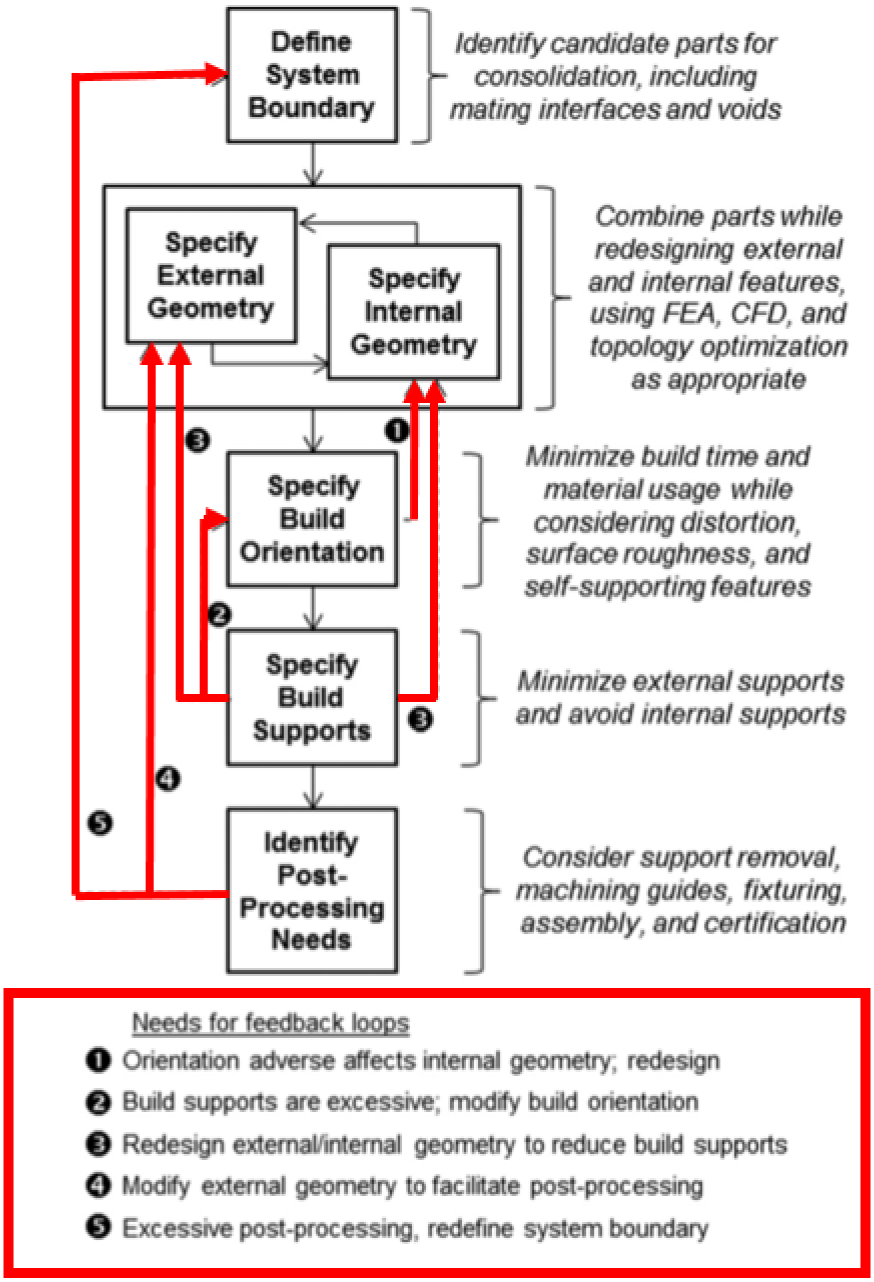


Figure **2-10**: The design framework Schmelzle et.al [6], Feedback loops highlighted in Red.

A recent addition to this list of frameworks came from a familiar research group in Italy. Two versions of the proposed framework from the group are shown side by side in Figure **2-11**. They applied topological optimization to a bracket, iterating as applicable to address concerns for the PBF-LB/M process, referred to in the study as L-PBF, until an "optimal" design that satisfied their criteria was produced. At that point, allowances for machining mating surfaces and additional features to aid in machining this "optimal" design were appended to the part. The considerations for secondary processes are effectively an afterthought, with no illustrated path for updating the "optimal" design should it be advantageous to do so. It works in the case of this simple bracket, but can break down when designing a more complex component or system.

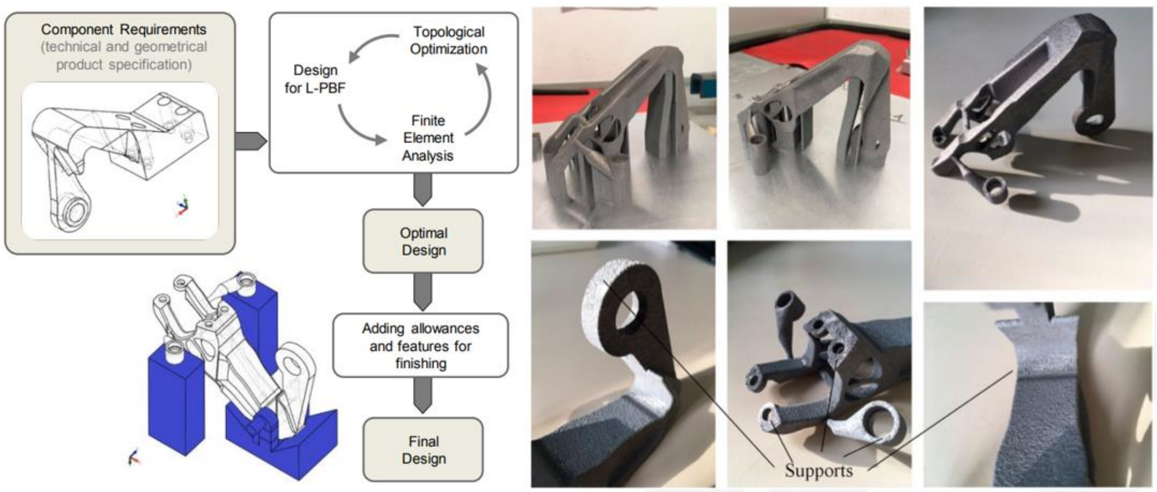


Figure **2-11**: Atzeni 2018, Design framework highlights when to add features to aid in machining

2.5. Parting Thoughts on Frameworks and Guides

Voltair is credited with saying "The perfect is the enemy of the good". Subject Matter Experts (SMEs) in industry will be tasked with knowing how best to redesign a part for AM and how best to consider secondary processes to satisfy requirements. Equally important, is the ability to recognize when AM is not the best solution. In all the frameworks analyzed, it was noted that there was no documented off-ramp. In industry, design efforts are constantly mindful of cost and schedule, and many of the frameworks presented are structured in such a way that they pursue a perfect solution for AM, irrespective of how long it is expected to take. In another case study, the redesign of a PBF-LB/M part was revisited after several years [27]. While knowledge about the material/machine limits and improvements in design tools made the process easier, the authors were keen to explicitly mention the following:

> What really made a difference are the methods to organize the workflow and to overcome restrictions, e.g. the early determination of part orientation based on an ideal design, together with design principles for easier post-processing [27]

The frameworks, design guides and case studies are critical in cultivating future DfAM engineers. Design engineers that can cost-effectively converge on the preferred part orientation and post-processing strategy early in the design process, and quickly assess whether or not AM *should* be applied in a particular situation will be a great asset to industry. This can drive down the opportunity cost of DfAM and further accelerate its adoption in industry.

Chapter 3

DfAM+ Framework

3.1. Introduction

DfAM+ is the extension of the definition of DfAM to include considerations for the following:

- Effort required in design
- Effort required in subtractive or secondary finishing
- Effort required in certification or verification
- Order of operations in the Manufacturing Process Plan (MPP)

The consideration of these concerns early in the conceptual phase of the design project was noted in the literature [27] as being beneficial to the successful development of a finished AM part. Prior frameworks explored in Chapter 2 were drafted after a post mortem analysis of the practices exhibited by the by the design engineer during the respective case study. To craft a framework or workflow that addresses the DfAM+ considerations, inspiration was drawn from the studies of systems engineering workflows [28]. The Vee Model, also commonly referred to as the V-Model for systems engineering was selected as the basis for the new framework, see Figure **3-1**.

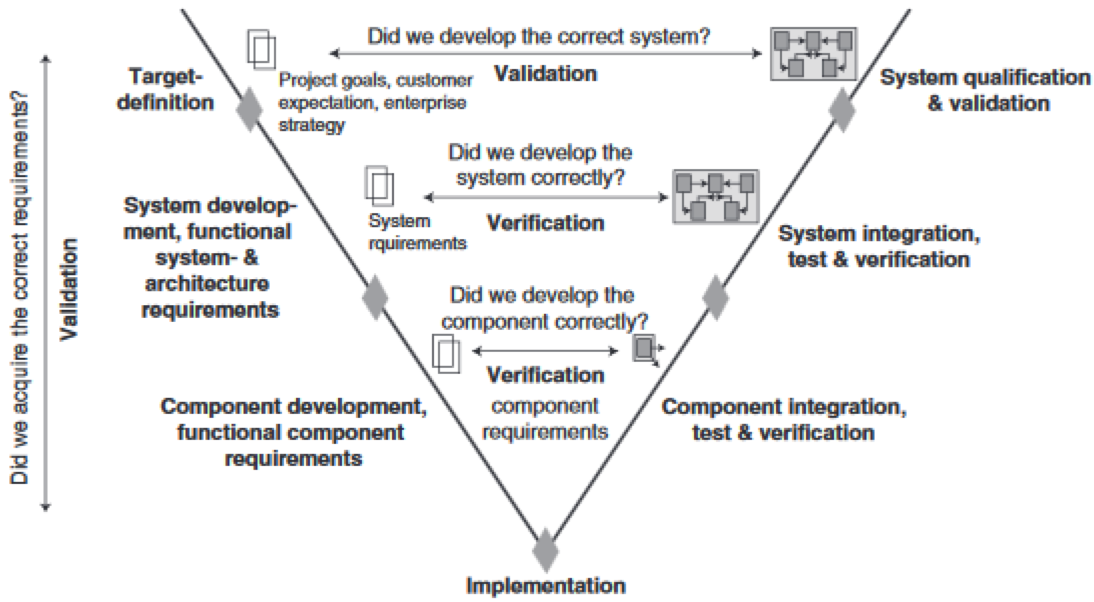


Figure **3-1**: The Vee-Model, a top-down bottom up approach to systems development [28].

The V-Model works by decomposing the problem, tracking requirements as the engineer drills down to smaller discrete components with their own requirements. Going up the right-hand side of the V-Model the small detail components are checked against their requirements before being integrated and refactored together. This continues until all the system components are properly integrated and the system can be compared to the original mission statement.

To address the need for a DfAM+ framework to scrutinize the applicability of AM, the left leg of the V-Model was modified to have off ramps, for if at any point the project is deemed unviable. By keeping as much of the discussion of requirements and design decision making at a high level, the knowledge work cost of evaluating the redesign effort can be kept to a minimum or abandoned if it is determined that the course of action will not satisfy the requirements in a cost effective manner. On the right side of the modified V-Model is where the majority of the design and product development costs are expected to be incurred. Starting with the detail features and integrating them together using the methods agreed upon when previously traversing the left-hand side of the V. This way design will only be undertaken if the concepts and strategies are agreed upon. There are rules and best practices for moving through the stages of the design framework, which are outlined in subsequent sections. The rough outline of the new DfAM+ framework is shown in Figure **3-2**.

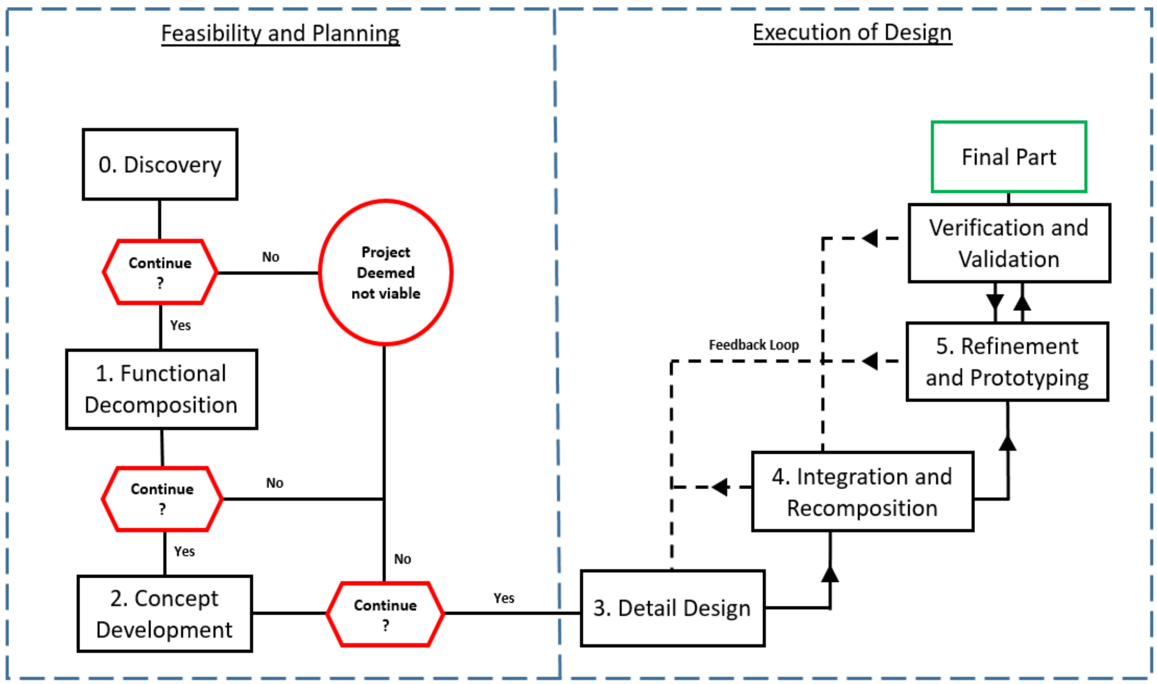


Figure **3-2**: The DfAM+ Framework, based on the V-Shape

3.2. The Framework Process

Figure **3-2** shows the phases of the workflow at a high level, with each of the phases having an explicit focus. In the **Feasibility and Planning** side of the framework, the intent is to systematically breakdown the problem with as little investment of time and knowlegework as possible. A check list is used to make sure that considerations beyond the successful additive manufacture are addressed before investing the time and resources in the execution side of the framework. The **Execution of Design** side is where the product definition is generated and the majority of the knowlegework is expended. By taking the time in the concept development phase to address primary and secondary machining considerations, the majority of mistakes can be caught and it is possible to converge on the final state of the part by the end of the **Integration and Reconfiguration** phase. This will roll into the **Refinement and Prototyping** phase where small details of the As-Printed state are adjusted for build success and with any adjustments to reduce the difficulty of primary and secondary machining will be incorporated. These adjustments are made until a successful part is produced through Additive Manufacture along with Primary and Secondary Machining that can be used to validate the design. The subsequent parts of Section **3.2.** explain these explicit phases in greater detail.

3.2.1. Discovery

In the Discovery process, the first stage in the design process illustrated in Figure **3-3**, a rough outline is set to apply bounds to the design space. As requirements are defined, concepts are generated regarding the specific manufacturing technology or combination of manufacturing technologies may be feasible to leverage to satisfy those aforementioned requirements. Any operating assumptions for the design effort are declared at this stage. These operating assumptions can include, but are not limited to, an expected minimum order quantity, expected production schedule, or the margins for budget and schedule for developing an approved and implementable solution.

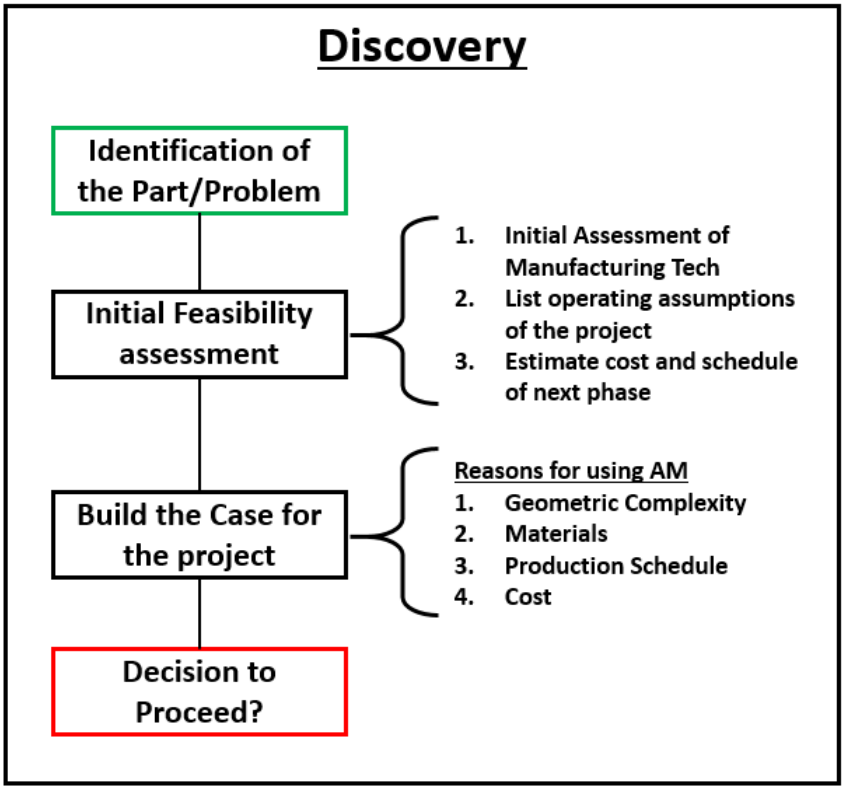


Figure **3-3**: The Discovery phase of the DfAM+ framework, illustrating an order of operations for the Discovery phase.

After an initial estimate of the cost and schedule for the various manufacturing technologies, including a variety of feasible AM technologies, articulating the assumptions used in justifying the use of AM is important. This is called “Building the Case for AM”, a list of valid rationale for leveraging AM is shown below.

- Geometric Complexity
- Materials
- Production Schedule
- Cost

The ability of AM to produce design with Geometric Complexity could be leveraged to reduce the part count in an assembly, or for products where there is no other way to achieve some desired result. Reducing the number of potential points of failure in a complex system is an excellent reason to leverage AM's ability to generate complex near-net-shape parts with minimal tooling. Reducing the required material removal can be helpful for expensive or difficult-to-machine materials, especially important for industries such as aerospace where "buy-to-fly ratio" is an important consideration.

If the AM technology can produce materials or properties advantageous or viable for a given application as compaired to another viable manufacturing process, that can be cited to justify the descision. For instance, Directed Energy Depostion technologies can be justified for its ability produce funtionally graded materials, e.g. wear resistant materials placed at a sliding interface, which would classify it as a "Materials" based justification. If a particular material system exibits better performance when produced with AM that could improve other design margins. It is expected that improvements in metalurgy in the AM space with further expand on users justifying their application via a "Materials" based argument.

Production Schedule justification can take a number of forms. Low volume production or the flexibility to customize the design as needed fall under this category. In industries where companies are trying to adhere to just-in-time manufacturing, AM can be justified as a means to minimize any shelf stock as the parts can be printed as needed. Spare parts are often only producable as long as the supplier maintains the tooling required for production. Leed time for AM as compaired to other manufactuirng methods can also serve as justification especially in cases where the demand is less predictable. If a spare part was designed originally for AM then the Original Equipment Manufacturer (OEM) can more easily accomidate intermittend the demand for parts as the cost for standing back up production would be lower.

Cost justification is not limited only the the base manufacturing cost, it consideres the costs over the full service life from cradle to grave. This could include the cost of sustainment, capital, labor, knowlegework saved by leveraging AM, the cost of downtime, and any other agrivating factors. Individual experience or design tools such as CAD software or design guides can play a role in how much the "Cost" of DfAM will be when compairing it to other methods. Sometimes this "Cost" justification can be used to explicitly set a budget for exploring an application of AM.

Creating a traceable arguments for the justification of using AM a project can be adjusted if those operating assumptions that led to that descision are changed. By requiring the articulation of the explicit justification for leveraging AM it aids in filtering out poor applications for the technology. The midset developed by better understanding the scope of the problem and the assumptions that led to certain descisions can inform the viability of any manufacturing processes used in conjunction with AM to satisfy requirements. If the budget for developing a product or the expected demand isn't sufficent to warrant lots of prototyping then design descisions will change to be in line with that expectation. Near-net-shape complexity may be less costly to produce with AM technologies but the knowledge work invested in defining that complexity should also be considered when evaluating if the benefits AM can provide outweigh any risks.

3.2.2. Functional Decomposition

Going from some amorphous concept from the Discovery Phase to a workable solution, depending on system complexity, can be a difficult task. Taking lessons from systems engineering, it is beneficial to discretize the problem into manageable pieces and assess requirements flowing from the whole to the individual features. Working under the principle that each functional requirement must be achieved by some combination of manufacturing processes in a MPP the target of this stage is to break the problem into manageable parts so the impact of various strategies can be assessed at the feature level and on the whole. See Figure **3-4** for an illustration of this phase.

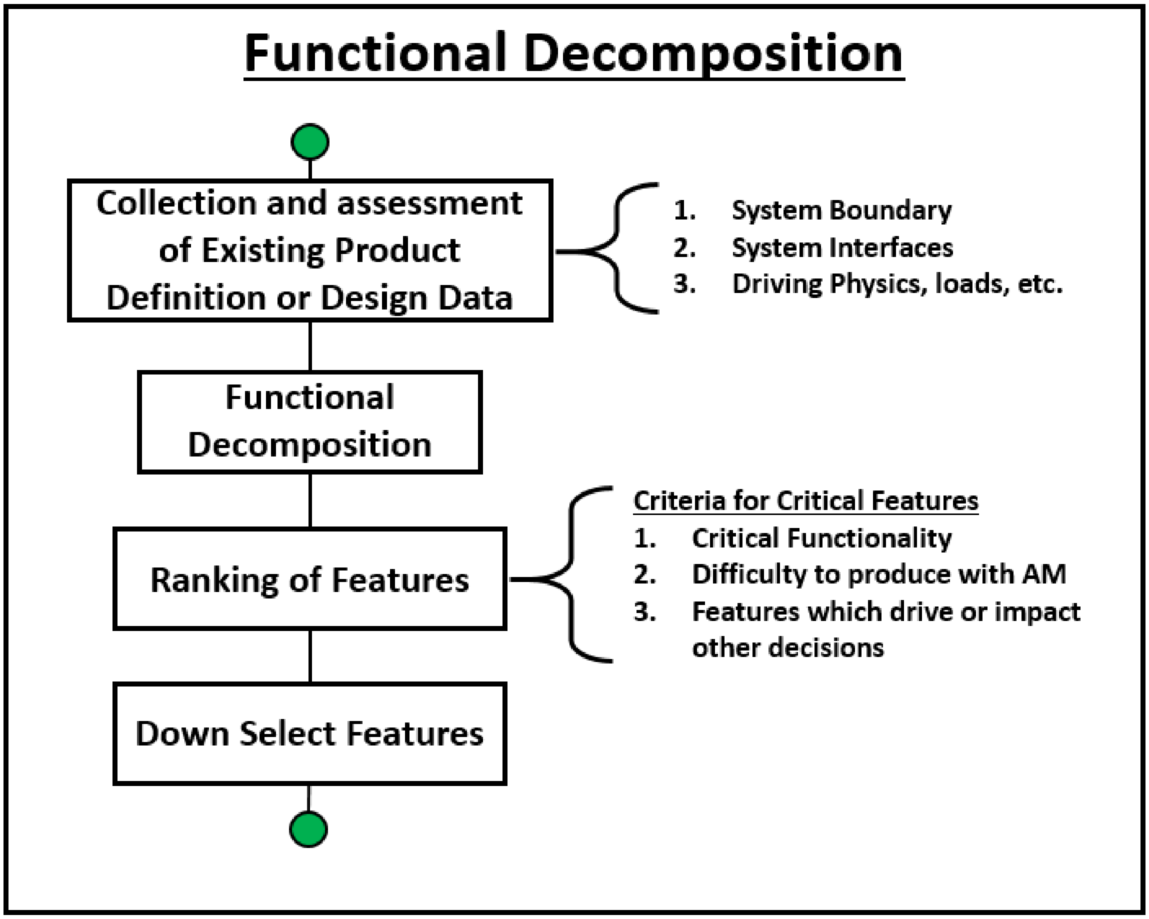


Figure **3-4**: The stages of the Functional Decomposition phase of the DfAM+ Process

Ensuring traciablility of these functional requirements aids in culling any unneccesary requirements and finding any troublesome requirements which may drive the design in a particular direction. Efforts should be made to decompose the part into broad descrete classes of feature where practical. For instance, interfaces which are typically machined may be broken up by required tolerance so that a strategy may be holistically evaluated as applied to all of them. While breaking up the features some may be deamed as less important or trivial, agnostic of the strategy leveraged on other features of the part. After Functional Decomposition it is important to rank the features so as to avoid getting lost in the weeds. The most impactful or functionally important features are loosly ranked along with any expected difficulty for achieving them with AM. From this list all the trivial descisions are removed from consideration and the target is to downselect to the few features which have the geatest impact on the rest of the design process.

Estimating the time and effort required to generate design concepts for the down-selected list of features can help in desciding at this stage if this effort is still worth exploring. At this point it is a judgement call, but having functionally decomposed the problem into it’s most difficult parts does provide a better perspective for this assessment. At the end of the day, to generate value the utility of the product needs to be greater than the sum of the effort expended in achieving it. When re-desiging a part for AM, if the expected improvement is less than the expected cost of exploring it further then there is no shame in electing to abandon the effort at this stage before more resources are commited unneccescarily.

3.2.3. Concept Development

Working with the down-selected list of features and their requirements, the Concept Development phase is focused on quickly iterating and evaluating variations of MPP strategies for achieving those requirements. The components of the Concept Development phase are illustrated in Figure **3-5**. It is advisable to pull concepts from prior work or available OEM published design guides where practical. Endeavor to limit the amount of knowledge work required to explore the feasibility of the design concepts. It takes time to use CAD tools to draft all the design concepts which can be a significant investment in knowledge work, where possible try to use sketches or markup of simplified geometry to think through the MPP concepts that are generated. Those low-knowledge-work means can permit a fair amount of insight for exploring design concepts while reducing the amount of resources invested to achieve those insights.

Be mindful that the scope of the design space and requirements may be negotiable or subject to change based on the results of exploring the impact of the MPP concepts. This is where having traceable requirements from the Discovery and Functional Decomposition phases can be helpful in evaluating if a requirement is needlessly contrite or should play a more pivotal roll in the rest of the decisions.

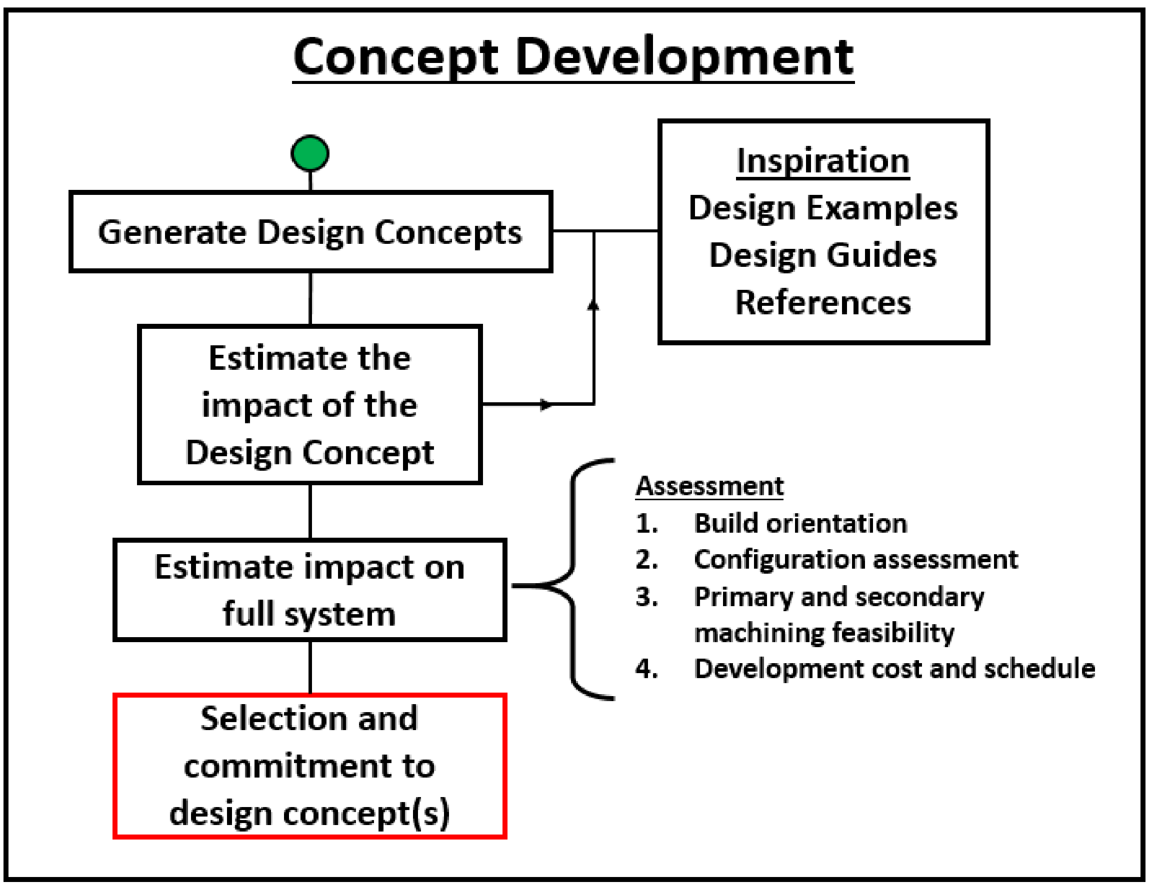


Figure **3-5**: The stages of the Concept Development phase of the DfAM+ Process

The moment a manufacturing process is leveraged for it's capabilities it comes with all its drawbacks and requirements. On the topic of MPP concept development there are a few basic guidelines as to the generation of practical concepts. First, MPP for explicit features can and often should be a mix of several manufactuirng processes where-in the order of operations is important.

AM requires more than just loading the machine and hitting print to get a successful part. The nuances of heat treatements - powder, part, and support removal are part of the metal AM process and need to be considered holistically with other manufacturing processes. For instance, heat treating prior to ensuring successful powder removal can cause the loose powder to sinter to the part and have unintended consiquences. These same types of holistic considerations are implicit when combining AM with primary or secondary machining processes.

A few of the considerations when leveraging Primary Machining with AM include work holding and locating the machining operation appropriatly in order to achieve the aformentioned functional requirements. Work holding is critical for providing access to the regions of interest and providing sufficent stiffness to reliably and predictably remove material. The complexity of the part is a significant factor in determining what kind of work holding and other tooling is required. A less organic or “optimal” shape produced through topological optimization may permit the use of a less expensive tooling where the marginal performance loss it trivial compaired to the reduction in net cost from primary machining.

Locating the machining operation appropriately on the near-net-shape is another concern for Primary Machining. When a machinist locates the part in the machining center, also known as indicating, they generate a local coordinate system from which the manufacturing operations are performed relative to. The ability to accurately and repeatably indicate the part has a direct impact of the ability of the primary machining process to achieve a desired GD&T (Geometric Dimensioning and Tolerancing) requirement. Primary Machining operations should be planned either relative to some series of datums, constilation of locating control points, datums on a fixture, or should be indicated locally to the feature itself being machined. The state of the part prior to machining is dependent on the residual stresses maintained during the prior steps in the MPP. This can play a roll in how much machining stock is required and what is the best strategy to indicate that machining operation. When generating any MPP design concepts that include primary machining it is important to state the strategy for indecating the operation. If a primary machining operation is considered limitations of tooling such as accessability should be considered when ascessing if a MPP strategy is practical. Noting if a design concept is invalid is just as important as generating a viable solution as the insight can provide confidence in the final descision.

Secondary machining processes also have their unique set of requirements for fixturing or manufactuirng process development. While an extensive discorse on the nuances of leveraging various secondary machining processes is outside the scope of this work similar consideration to what is present in Primary Machining do present themselves. Nominally they contribute greatly to the the expected time required for manufactuirng process development as many of these processes are require to be “walked-in” through use of a DOE. If the requirements on the feature and the nature of the secondary finishing process would neccessitate modification of the up-stream as-built state of the component, then antisipate a significant increase in the resources required to bring that design concept to market. Performance requirements may nescessitate such a descision, but the requirements that drive to consider such an endevor must be strictly scruitinized and weighed against the risk. This may be a viable choice when it comes to high complexity, high value, high production volume applications where the expected return on investment affords a greater budget for product development. Such as the case for products similar to the GE-Leap fuel nozzle, where geometric complexity dominates the justification for leveraging AM instead of low volume production. Do note, each Secondary Machining process may neccesitate prep or post operation cleaning. Such is the case for Abbrasive Flow Machining (AFM) where the visous media would need to be removed from the part prior to service. As such, planning where to insert Secondary Machining processes is a descision which must be carefully reasoned through. An example of where a Secondary Machining process may be incerted in a conventional MPP involving PBF-LB/M with Primary Machining is shown in Figure **3-6**.

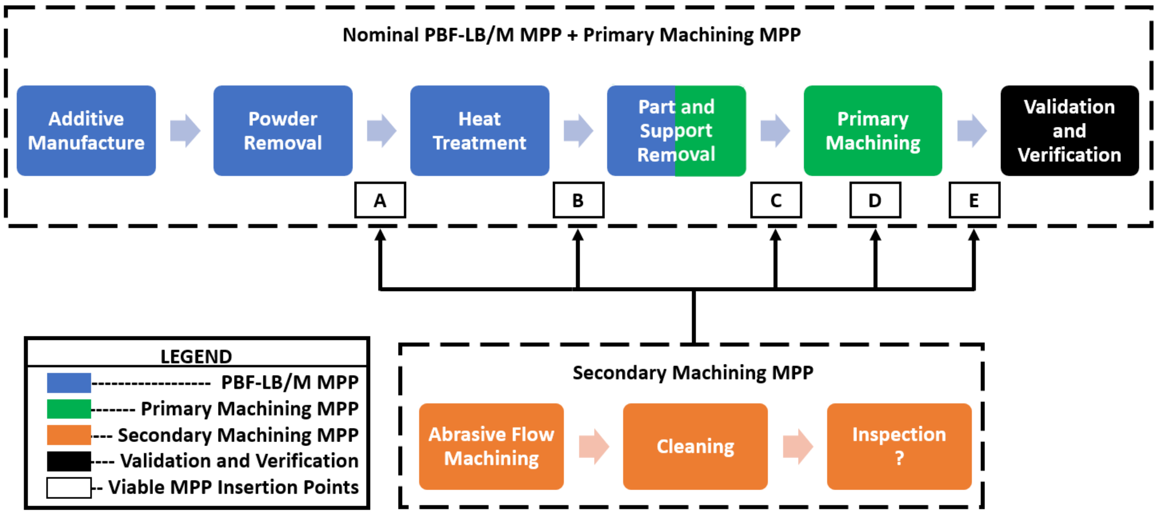


Figure **3-6**: Flowchart representation where in a nominal PBF-LB/M + Primary Machining MPP would feasibly insert a Secondary Machining MPP such as Abrasive Flow Machining in positions A-E.

The generation of feature specific MPP must include an agreeable method for Verification and Validation of the requirements which drove the conception of the MPP for that feature. The cost of the method intended to verify said requirement is considered along with an estimate of the effort required to complete a detail design of said concept. Generating an “exact” estimate of the cost is not needed, only the ballpark or high level estimation so concepts for each feature can be comparied relative to eachother. For instance, a surface finish and form error requirement could be applied on the inside of a through passage to improve the headloss or reduce the risk of debris. This may neccessitate using AFM to touch up those surfaces. The surface finish callout could be inspected through either distructive evaluation or through CT scan can be cost prohibitive. An alternative inspection method may be having a test stand that directly measured head loss or a witness certification that AFM was performed per some specification in the case of debris cleanup. Those later options would be more cost effective and may be sufficient to provide the confidence that the intent of that requirement is met. In general it is best to directly tolerance and inspect a requirement instead of trying to indirectly or arbitrarily ensure it's intent.

The contribution of the feature specific MPP concepts on the margins for achieving the higher level requirements, or the margins for other features are considered when generating a high level list of the pros and cons for each concept. There are margins for the effort required for detail design, the relative cost or dificulty for primary and secondary machining, and the impact on development schedule. The list of pros and cons doesn't need to be too extensive, only enough to draw high level distinction between each of the alternatives. This analysis of alternatives, especially when there is a large varience in the available MPP and expected results for a particular feature or function requirements, should be documented and considered as Trade-Studies.

When evaluating the pros and cons of various feature specific MPP it is important to understand the impact of that descision on the other features and the intended system configuration as a whole. Generating a rough representation of the proposed product architecture can aid in better understanding the impact of build orientation. If redesigning a component or assembly it may be benefitial to import and use the original design to make these assessments. Automatic generation of support material can aid in identifying where the part may need to be modified to make it printable. Running those low fidelity concepts through a build simulation software can provide early insight into margins for material usage, residual stress, and other problem areas. Strive to expend as little knowledge work as required to evaluate any proposed architecture and build configuration.

An example of this in practice for a series of complex internal passages, the location of the interfaces and the paths taken may be modeled as a simple circle even through the final geometry would be intended to be a more complex, self-supporting geometry respecting orientation of the build as demonstrated in the top half of Figure **2-9** [6]**.** It would take significantly more effort to evaluate each build orientation if the concept had to be fully detailed prior to assessing the feasibility. While genuinely informative, assessing and rationalizing through the impact of alternaitves conceptually can reach similar conclusions with drastically less effort. It is helpful to consider the phrase “time is money” when considering all the knowledge work that can go into designing a part can be factored into the final cost of the part on top of the manufacturing cost.

Early convergance on an perfered build orientation was noted as a key factor in improving the DfAM process [27]. Hence, any down-selected feature where the requirements informing the concept generation would dominate the criteria used in selection of perfered part orientation are descided first. This may eliminate a number of design concepts for the subsequent features, which can help make the descision process more straight forward. Systematically working through and commiting to a design concept or MPP for each feature, builds a rational roadmap forward for detail design work. If performed correctly the risk of late finds which would neccesitate starting over from scratch and the requirments are reduced to a practical level. A lesson pulled from the study of systems engineering is that late changes to requirements are often associated with cost over-runs or the generation of an ineffective solution. While it is not impossible to adjust the functional requirements after this stage, it should be highly advised against as doing so should neccesitate re-evaluating concept development phase, possibly invalidating much of the work prior to that modification. The point of the systematic approach of the prior phases is to minimize that risk, or better accomidate it should that uncertainty be present.

To this eng, each requirement in the down-selected list needs to have a commited, or at least, a tetative and a backup MPP concept agreed upon prior to proceeding to detail design. An adjustment to the design space may midigate this issue, a reminder that not everything can or should be additively manufactured. Given the more concrete path for the task at hand the estimate of the effort required for implementation can once again, be weighed against the benefits. If the calculus is still in favor of the effort, then proceed with expending the knowledge work and resources to bring the concept to fruition.

3.2.4. Detail Design to Integration and Recomposition

The act of translating the decided upon design concepts and the accompanying MPP into some CAD suite is the focus of these two phases. The line between Detail Design and the Integration and Recomposition phases is rather blurred. In earlier phases the problem was broken to several discrete features and requirements were allocated to those features. These discrete features are merely small parts of a larger whole, or intended final state of the part. Integrating these details in a coherent manner may require some recomposition. Hence a tight feedback loop is illustrated between these two phases in Figure **3-7**. It is helpful to distinguish these phases by the focus of the design effort. The Detail Design phase is where the focus is on those features are defined on their own to satisfy the feature specific requirements. The Integration and Recomposition phase is focused on combining those details into some desired final state of the part while satisfying the higher level requirements which may not have flown down to the discrete details.

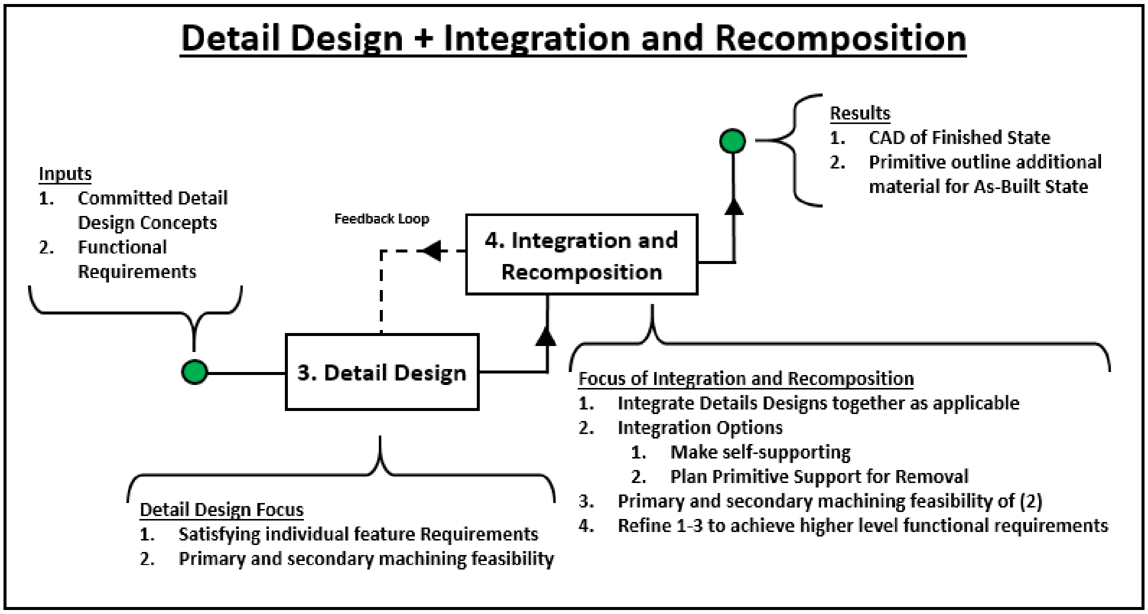


Figure **3-7**: Illustration of the Detail Design and Integration and Recomposition design phases

While undergoing this effort, if the MPP for a particular feature neccesitiates primary or secondary machining it is wise to roughly mock up any machining stock or support geometry seperately from the final state of the feature. Consider the limitations or requirements of any primary and secondary machining process while mocking up this excess material. The inherant ability of CAD to allow users to design in context with multiple bodies is a boon.

Practitioners familiar with workflows associated with applying Topological Optimization to a design would consider their workflow broken up as follows. The non-design spaces are defined in the Detail Design phase. The Integration and Recomposition phase is where the generative design space connecting the details is defined and subsequently the optimization is performed. The Integration and Recomposition phase would be complete upon combining the generative geometry with the details to form the intended final state of the part as a single manifold body.

The design of the final state can be measured up against it’s requirements via simulation or through prototyping in the case of checking the form and fit of the product. Systematically working up from the details in this manner should aid it catching pitfalls in the primary and secondary machining processes by forcing their ponderance earlier where design changes are less expensive.   Any loosely mocked up machining stock and support structure applied to the details is kept separate from this final body but is not expected to be in it’s final form. Refinements to these other bodies for the sake of the as-built state and for the benefit of the other steps in the MPP are the subject of the next phase of the DfAM+ process.

3.2.5. Refinement and Prototyping

The rough mock up of the machining stock and support structure, while useful is expected to be far from complete. The focus of this phase of the DfAM+ process is definition of the as printed state and the successful execution of any part of the MPP beyond the Additive Manufacture. It is the penultimate phase of the DfAM+ effort, as illustrated in Figure **3-8**. Not all features may be appropriately supported at this time and modifications may be necessary to accommodate powder removal. Better facilitation of the requirements associated with primary and secondary machining are expected to be a significant driving force in the form of this materials that intended to be removed.

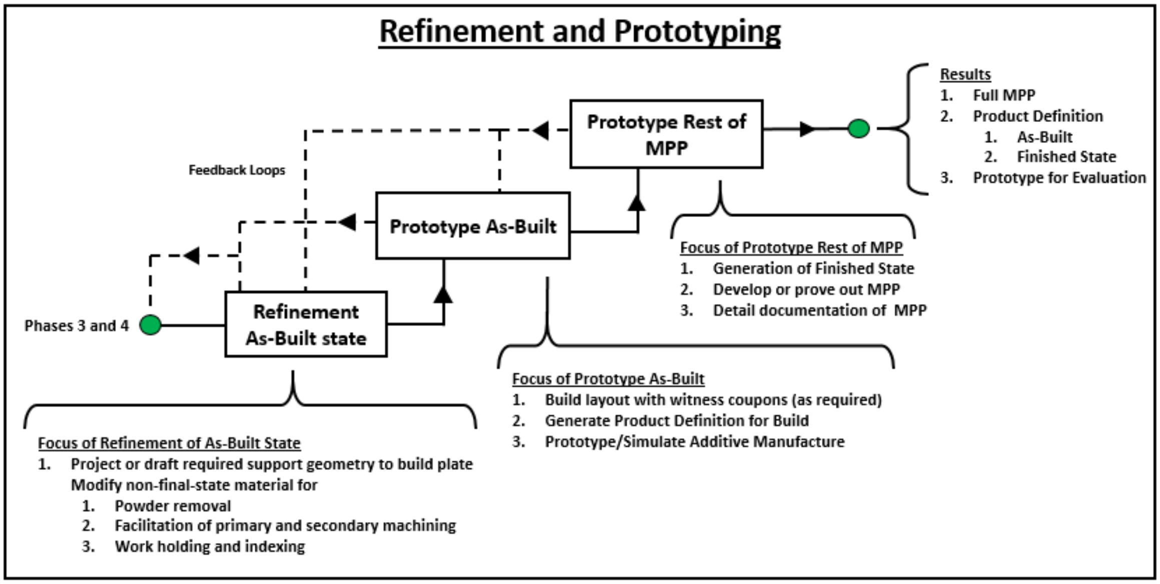


Figure **3-8**: Illustration of the Detail Design and Integration and Recomposition design phases

There is an opportunity to modify the intended final state to simplify machining processes or reduce the cost the necessary tooling via the use of a feedback loop. This can be beneficial especially in the case of permitting the use of less expensive work holding or drastically reducing the machining time by reducing the complexity or number of a machined surfaces. The decision to leverage this feedback loop should be based on either a value proposition or by necessity. In the case of a value proposition the change in the performance metrics of the final part need to be worth and increased effort required to enact the modification. Note, the costs associated with post processing is embedded in the calculus of the expected performance metrics of the final part. In the unfortunate case of the feedback loop being required by necessity, provisions are made in the framework to move back even as far as the Detail Design phase.

Once the rest of the material comprising the As-Built state has been generated and checked for errors the next step is to export the necessary product definition. Note that any support material not intended to be solid should be exported as a separate body so that it can be used in generation of lattice or breakaway support material. Alternatively non-solid support material can be generated ad-hoc in the software used for build preparation. First, a model of the Finished-State of the part. Second, after joining all the bodies comprising the As-Built state together with the Finished-State body exporting it for designing work-holding and applying toolpath for primary machining. Last is the generation of the build plan. If witness coupons are to be incorporated into the build they are laid out in either in the CAD suite relative to the build system coordinates or the build plan is generated in the tool pathing software. Once a satisfactory build plan has been generated it is document and exported.

A final check in a build simulation suite such as Autodesk Netfabb^{tm} is advisable as it is typically less expensive than a failed build. The automatic checks are not infallible there for, a full prototype of the build plan is often necessary to build confidence in the As-Built state of the product. Especially if the intent is some kind of a first article certification.

Prototyping the rest of the MPP occurs at this stage. This includes the generation of any support equipment such as work-holding for primary machining or fixtures for secondary machining processes. Note that many secondary machining processes will require extensive prototyping to dial-in the process. If leveraging these kinds of secondary machining processes it is not advisable to declare the DfAM+ process complete until the process is proved out and the necessary controls are documented.

At the end of this process all the necessary product definition required for the MPP is generated. If a first article is required then at this point it has been produced in accordance with the MPP and accompanying product definition. The next step is ensuring that the product as produced satisfies the requirements derived and agreed upon in phases 0-2.

3.2.6. Verification and Validation

Until the design is tested against its requirements this whole effort is effectively theoretical. Verification is the act of evaluating the component against the letter of the requirements derived and agreed upon during phases 0-2. Validation is the test of the component in the intended application where its performance and discrepancy is scrutinized. While they may sound similar, the process of validation permits the testing of the component against any requirements of the service life, not adequately captured in the design requirement.

There is an opportunity for feedback and modification of any of the prior phases but depending on where and what that discrepancy is, it could be cost prohibitive to address. Depending on the measure it is always possible to conceive of ways to improve the design or the manufacturing process. If the product satisfies the Verification and Validation, along with adhering to the rational used in the initial justification for leveraging AM, then there should be confidence that the design is ready for full rate production.

3.3. DfAM+ with Stakeholders

In industry, rarely is any single engineer tasked with all the rolls and responsibilities necessary to execute a complex design effort and carry it to manifestation in the physical world. To this end, the generic DfAM+ process outlined in the prior sections is divided up more explicitly between multiple participants or stakeholders. This is to include members whom would nominally be charged with taking requirements and by execution of manufacturing processes satisfy those requirements. The proposed generic descriptions of the stakeholders of the DfAM+ framework are the Design Engineer, Subject Matter Expert (SME), Technical Authority (TA), and Manufacturing.

The Design Engineer takes point on much of the knowledge work used in defining the geometry of the part. Some competency with Conventional Manufacturing and AM is expected. They will be performing most of the detail design work and responsible for product definition, and be expected to interface with manufacturing personnel as necessary.

The SME is by no means limited to a single entity. Typically this is an engineer particularly versed with the application being addressed by the design effort, i.e. if the design effort is a part of a jet engine then this SME is someone who is responsible for the pertinent section of the engine being designed. Another kind of SME is a decision support SME, this can be a materials or analysis type engineer which can contribute to the design effort as auxiliary personnel which is consulted for their relevant expertise.

The TA is the approving entity for the design effort. Final calls, particularly those related to technical conscious or large systems level decisions are made by this participant. They fill an antagonistic roll, keeping mindful of the margins for success or failure of the project. Final acceptance of the design, and any intermediate decisions, is deferred to them as they are the keepers of the Verification and Validation phase. They often act as the superior to the primary SME support the design effort. The decision gates pertinent to preceding from phase to phase belongs to the TA.

Manufacturing is the term for the production personnel representative fielding many of the hands on feasibility questions. Later they will be responsible for executing the design intent escribed by the Design Engineer. Their participation is crucial so as to incorporate their insight into MPP related decisions. They are considered an authority on the manufacturing capabilities they are responsible for in the case of production artisan such as a machinist. A manufacturing planner is also beneficial in this roll as they are capable of making quick rough estimates on the cost of a MPP before it is initiated and are empowered to make suggestions to improve those costs and minimize the risk of failure of post processing activities.

The subsequent sections outline how members, embodying the rolls of these stakeholders, may best coordinate with one another. Participants should not consider themselves limited to playing the roll only one stakeholder. Conversely, multiple participants may be required to effectively service the rolls of a particular stakeholder, as is the case for the SME stakeholder. A clear breakdown of which participants are assuming which stakeholder roles and responsibilities is important. Unambiguous communication and decision making, particularly in the Concept Development phase is crucial for the success of the DfAM+ effort.

3.3.1. Discovery

Discovery is the inception of the initial design effort. The scope of the manufacturing application is documented and a first pass at relevant manufacturing technologies is proposed. During this phase relevant technical data is collected, a case is made, and a budget for allocating resources to the next phase of design is brought to the TA for approval or the TA is made aware of the effort if they have delegated such authority. Any comments or concerns the TA may have are given to the Design Engineer and SME to be addressed in the next phase.

3.3.2. Functional decomposition

The Design Engineer and SME dissect any pertinent tech data and begin to functionally decompose the project into features or sub-systems. If the SME is aware of any expected issues from a similar application then they are charged with relaying those to the Design Engineer. Critical characteristics of the system are identified at this stage by either the SME or TA. The SME after functionally decomposing the problem rank them in terms of importance. The Design Engineer down selects to pertinent features for discourse based on individual feature difficulty and if any feature is present which would have far reaching impact on the strategy for producing other features. The TA or SME may also interject a feature of articulatable concern to them.

3.3.3. Concept Development

The Design Engineer takes these pertinent features and generates a series of MPPs to satisfy the feature specific requirements. Taking care to minimize the investment of knowledge work by keeping the analysis and discourse at a high level. Feasibility of the generated concepts are run by both the SME and Manufacturing. A rule for any concept generated is that it must be accompanied by a satisfactory method of verification or validation where applicable. An example of an applicable verification method for internal complex passages is the option of commuted tomography (CT) or test plan to verify the expected head loss from the complex passage, these options may play a role is the decision-making process. If a proposed concept is deemed impractical the Design Engineer is responsible for articulating that design review. Once the SME and Design Engineer agree they are ready to present their concepts to the TA then a meeting is convened to discuss the evaluated concepts and lessons learned from any supporting trade studies. Any concepts which present a risk of interactive process development is highlighted as a risky design concept. If the TA concurs with the presented DfAM+ MPP and design strategies would reasonably satisfy the requirements and scope of the project then the resources are committed to the effort and detail design can begin. One of the most important outcomes from this stage is setting the build orientation as minor adjustments in orientation could kick off knowledge work intensive and costly geometry changes.

3.3.4. Detail Design to Integration and Recomposition

Working backwards through the functional decomposition on the detail design of the features most troublesome features to the least impactful feature debated with the TA. For the detailed features with verifiable characteristics at this stage of detail design the SME is kept apprised of the progress and results. The SME has the discretion to run specific detail features by the TA if they feel the need. This is especially important if a detail design is produced with some concession from it's agreed upon detail level requirements. Once the SME has acknowledged the any detail features which satisfy their respective requirements then they are free to be integrated together at the Design Engineer's discretion. Recomposition occurs when the way the discrete features may not cleanly integrate together may necessitate the modification of a previously green lit detail design feature.

At this stage some features may already have some allocation for post-processing or support material. The target at the end of the Integration and Recomposition phase is model which reasonably represents the final state of the part after post-processing with any allocated support material hidden. This is useful for if there are some requirements intrinsic to this stage of the part which need to be evaluated. A rapid prototype of this stage of the model may be advisable to catch any unforeseen issues or necessary adjustments. As the Design engineer is planning out subtractive post processes they are coordinating with manufacturing to ensure post processing is no more risky than it has to be. If given the green light by either the SME or the TA at this stage them it's time to transition to focusing on Refinement and Prototyping.

3.3.5. Refinement and Prototyping.

Any geometry not adequately addressed by support material is addressed at this time. The Design Engineer transitions to adjusting any support material for either powder removal concerns or in conjunction with the Manufacturing representative. If there are adjustments which would affect the expected end state of the part but would drastically reduce the cost of post processing those are brought up with the SME or TA as applicable. If possible, all adjustments to aid post processing are to be limited to material not intended to be left on the part. When the Manufacturing representative is satisfied with post processing strategy for fixturing, indicating, and machining then it is there prerogative to initiate the generation of any necessary tooling.

Prototyping the As-Printed state is initiated. Up to this point great care has been taken to minimize the risk of needing to adjust any of the detail design features or the design of the finished state of the component as those adjustments can be arduous depending on the state of the modeling tree and the methods employed by the Design Engineer. The risk is ever present for the initiation of a feedback loop to stage 3 or 4 of the design. However build failures at this stage are more likely to be isolated to adjustments to the support material. If possible, simulate the build to assess the distortion and risk of a failed build. Prototyping is still considered to be underway till the component passes first article inspection after post processing.

3.3.6. Verification and Validation

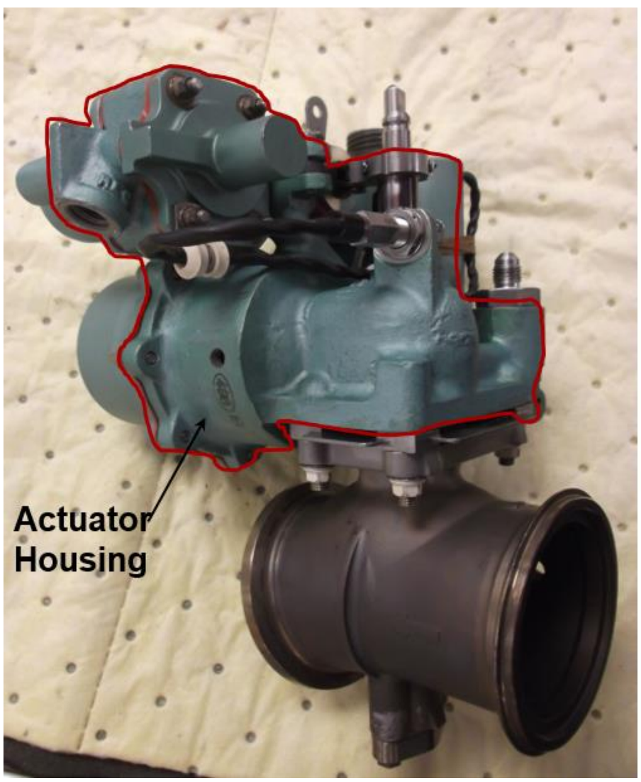
Verification is in essence the first article inspection as this is checking the first article against the product definition. The SME and TA are to evaluate if the design as produced satisfies those systems level requirements derived during Discovery. Depending on the requirements to satisfy Validation, full destructive evaluation or controlled performance evaluation, final sign-off is dependent on satisfactory evaluation of the TA. The Design engineer is on standby should any modifications be directed by the SME or TA. Once the TA signs off the design then a final part along with its MPP is locked in and becomes revision controlled.

Chapter 4

Case Study: The Pressure Bleed Air Regulator Housing

4.1. The Challenge

The Pressure Bleed Air Regulator Housing, also known as the PBAR Housing, is a complex machined casting with several interfacing components. It possess machined and back capped internal passaged which divert high pressure air from the aircraft engine to various flight-critical sub-systems. The part is difficult to procure and the soft aluminum which comprises the casting is prone to damage and requiring repairs.



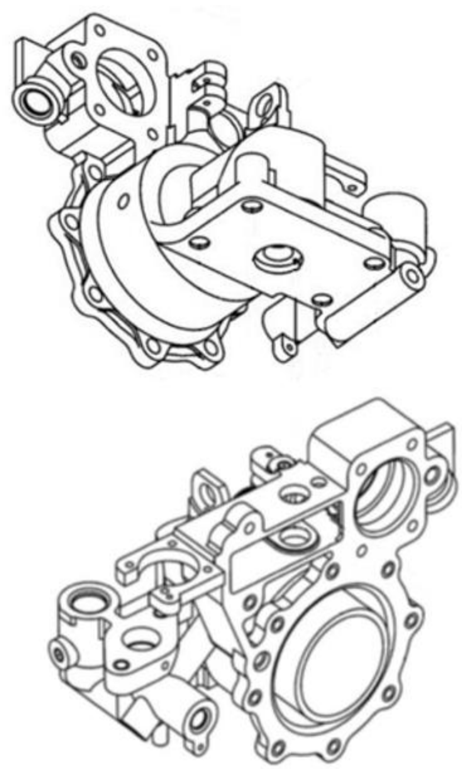


Figure **4-1**: Photo of an assembled actuator housing on left, two iso view sketches of the housing shown right.

NAVAIR commissioned the exploration of standing up a new source of supply for this component. The team at CIMP-3D was brought on to handle the nuances of an initial design that utilized PBF-LB/M for fabrication. CIMP-3D contributed the personnel that served in the Design Engineer role, with NAVAIR providing the rest of the stakeholders. The SME stakeholder was provided by working level Fleet Support Team (FST) engineers, typically mechanical or systems engineers, familiar with operation of the subsystem the PBAR housings belongs to. The FST retained the ability to call in additional SMEs from their ranks, whenever the working level engineers required, and could solicit a second opinion from other disciplines such as materials engineering. The TA stakeholder was fulfilled by a senior engineer, cognizant and responsible for the safety and signoff for this part of the aircraft. As the intent was to have NAVAIR perform the machining operations, NAVAIR facilitated access to the manufacturing personnel that would be tasked with primary machining of the as-built additively manufactured part.

Limited product definition is available for this component, and even less would be provided to the design team on the basis of simulating a common scenario within Naval Aviation Sustainment, where original product definition may be scarce or erroneous. Given this framework, the team initiated the Discovery process, see Figure **4-2**, to gather the information necessary to inform the redesign for AM process.

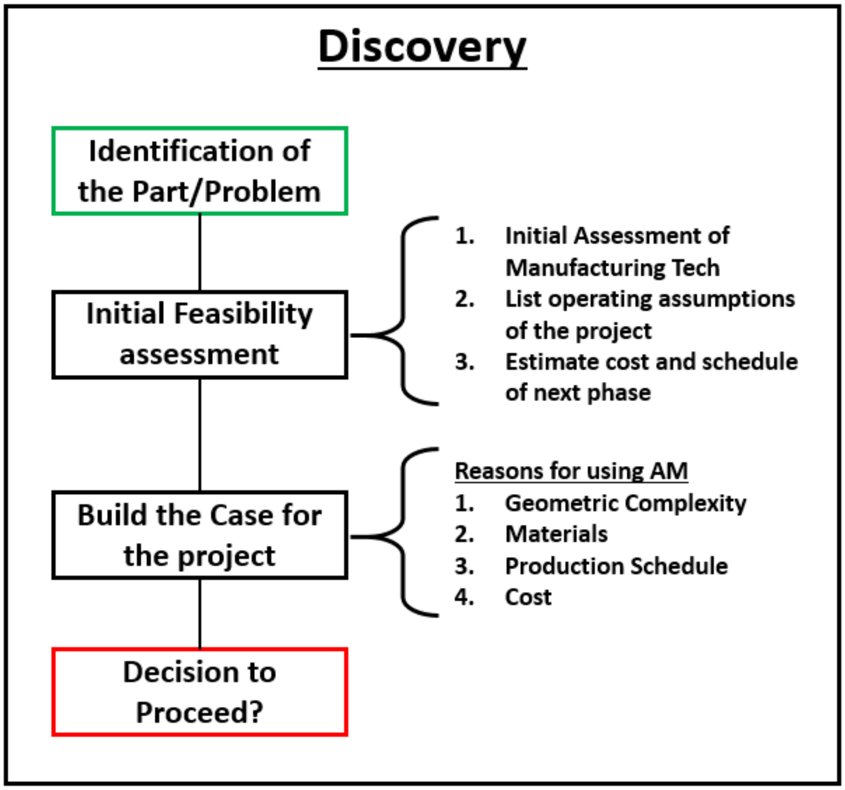


Figure **4-2**: The Discovery phase of the DfAM+ framework, illustrating an order of operations for the Discovery phase.

As this would be an exercise to build an understanding of the effort and decisions required to facilitate DfAM for PBF-LB/M, the assessment of alternative manufacturing technologies was culled. The decision gates built into the framework to facilitate abandoning the design effort were similarly short circuited to eliminate any and all decisions that would normally be considered necessary prior to redesigning the part for AM. Interactions with the TA were to be documented and conducted in a manner that ensured their willingness to accept a component designed using this framework as airworthy. This constraint on the design process was critical to better emulate the rigor required in design efforts undertaken within the NAVAL Aviation Sustainment community in pursuit of airworthiness.

4.1.1. The Discovery Process

Identification of the part/problem as well as a basic feasibility assessment was carried out by NAVAIR prior to initiating this joint effort with CIMP-3D. As part of NAVAIR's prior effort, a CT scan of the target component was generated. Given the minimal information provided to CIMP-3D, time was allocated to extract as much of the existing product definition as possible from the scan data to inform a feasibility assessment and gather information that would normally be extracted during the Part/Problem Identification step of the Discovery phase, see top half of Figure **4-2**.

The task was to reverse engineer the component from a CT scan and scrap article, and then work with NAVAIR to re-design the housing for PBF-LB/M. The intent is to produce a drop-in replacement to enter the supply system with as-good-or-better material properties than the original casting. The more changes required in the new housing design, the more challenging it would be to certify, so the direction was to change as little as possible. As a result, the following requirements typically not associated with DfAM efforts were explicitly defined:

- Maintain the original mass
- Maintain the location of the center of mass
- Change only what it absolutely necessary to make producible with PBF-LB/M

Considering this is a critical application aircraft part that feeds various important sub systems, and the fact that there is little-to-no design or performance data, the hesitancy to change anything at all is actually a somewhat rational position.

The reverse engineering was performed in Geomagic Design X via sectioning and tracing over a mesh generated from a CT scan. A physical article was also interrogated whenever information not resolvable from mesh was extracted, such as surface finish and thread specifications.

While parametrically modeling the casting, two features were noted to require significant re-design to enable fabrication via PBF-LB/M: the Actuator Cavity and the Internal Passageways. It was determined that decisions related to the Actuator Cavity were going to be one of the most challenging features and would likely be the deciding factor behind print orientation. While this kind of identification and decomposition of critical features is more commonly associated with the Functional Decomposition phase, this kind of information can be gleaned early in the Discovery process, especially when reverse engineering is used as a tool to generate new product definition to inform the redesign effort. It required roughly 200 hours to create a parametric CAD model from the CT scan data. The generated files would prove useful as construction geometry for modeling a re-designed part, as well as for simulating distortion and identifying which features needed support structures. When the density of the aluminum powder and the capacity of the powder reservoir in the EOS M280 were considered along with the size of the PBAR housing and the necessary witness coupons for build verification to ensure quality, there were only two viable build orientations. The orientations considered were simulated in Magics and the anticipated distortion of the builds were simulated in Autodesk Netfabb, see Figure **4-3**.

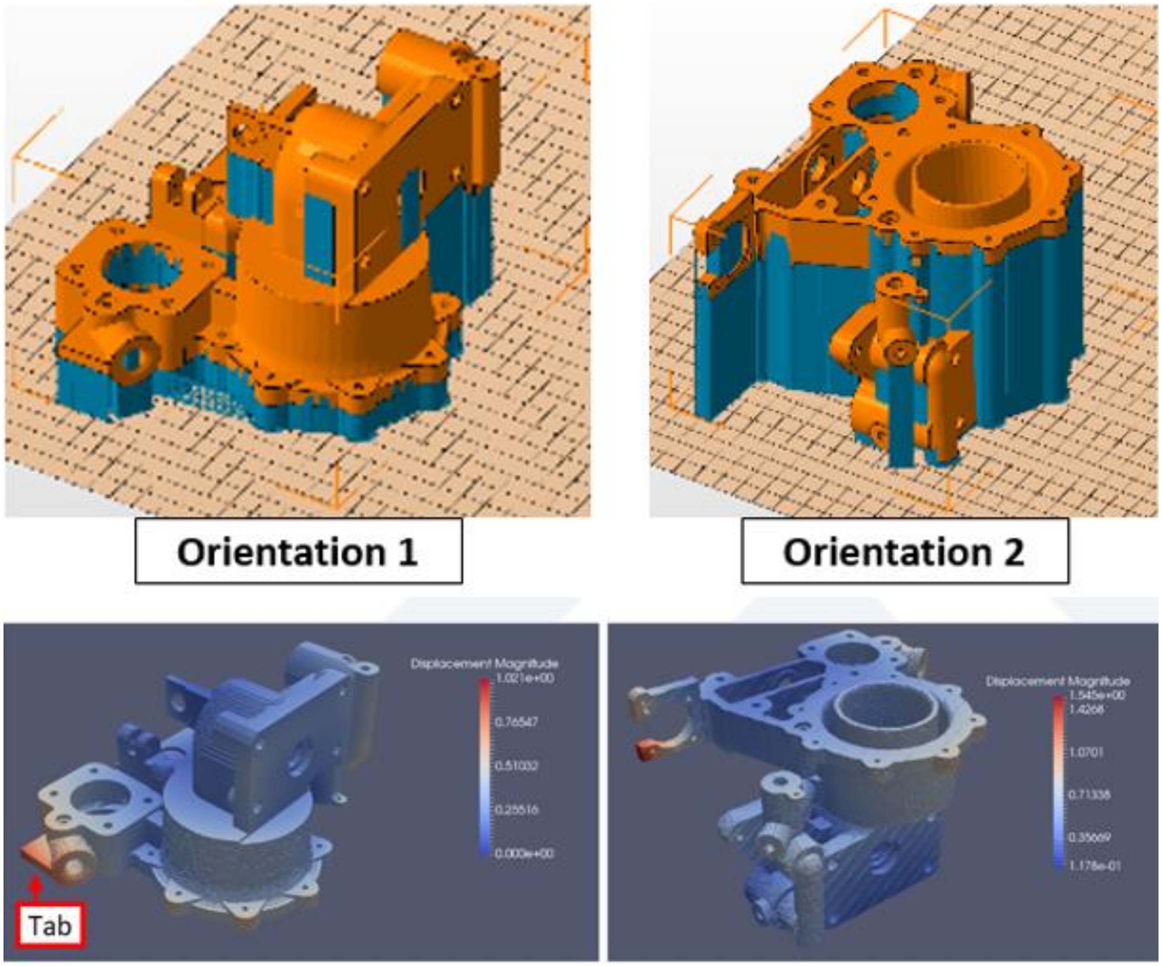


Figure **4-3**: Magics auto generated solid support generation shown in Teal, Autodesk Netfabb build simulation shown below. The maximum displacement caused by residual stress belongs to orientation 2.

Due to the results of the simulation and being in pursuit of a greater margin for adjusting the location of the final design's center of mass, inquiries were made about the Tab (denoted in the figure). Finding that the Tab served no purpose and was likely left over from the original casting process it was culled with NAVAIR's consent. This would make the challenge of redesigning this part to satisfy the mass based constraints, much easier.

4.2. Functional Decomposition

During the Discovery process, information was extracted to help inform the Functional Decomposition phase, Figure **4-4,** of the DfAM+ process. The following sections highlight the specifics regarding how discrete features or functions were decomposed. Specific details about the functional decomposition were addressed discreetly in what is referred to as the "Embodiment". The Embodiment is the understanding of how a particular feature or function were achieved on the original article. Understanding the MPP that created these features on the original part can help inform any discussion of how the functional requirements of the original may translate to the redesigned part. For instance, any machined interfaces will most likely be maintained as machined interfaces. Surfaces which were left in the as-cast state on the original part may be candidate geometry for as-built surfaces to remain untouched by primary or secondary machining processes in the additively manufactured design.

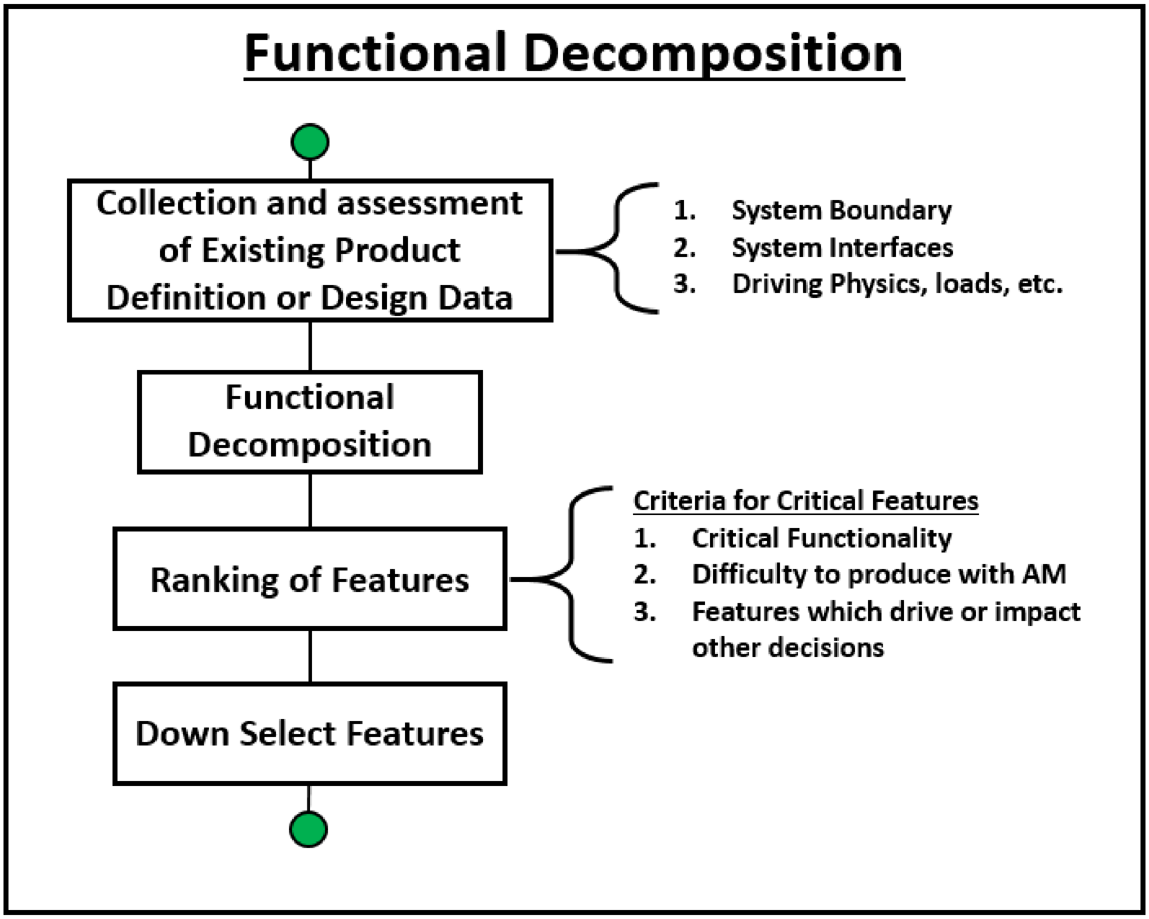


Figure **4-4**: The stages of the Functional Decomposition phase of the DfAM+ Process

When functionally decomposing the original, the degree to which the design will be decomposed must be carefully considered. It isn't helpful if every face of every machined geometry on original is discussed ad-nauseam and decided on individually. The surface finish on the majority of the mating faces was substantially similar, allowing these faces to be grouped such that the strategy for each can be considered at the same time. It was also noted that the strategy to achieve these features was unlikely to be dependent on design of other features, so all the traditionally machined interfaces were eliminated from the list of features to be addressed during concept development. The features that were down selected to be studied and debated during concept development were the "Actuator Cavity" and the "Internal Passages".

4.2.1 Functional Decomposition of the Actuator Cavity

Per the DfAM+ framework the actuator cavity was functionally decomposed. Much of the shape likely stems from the fact that an arm is assembled inside the cavity and swings during operation. The internal cavity pads on either side of the centerline of the cavity help locate the arm and provide enough material for bushings to be installed in either side. The material surface that makes up the inside and outside of this feature presents the same as-cast surface texture, implying it was not subjected to any primary or secondary machining. The form of the interior of the Actuator Cavity was generated from several orthogonal cross-sections extracted from the CT scan data in Geomagic Design X. The FST and TA were explicit that the volume of this cavity was suspect to play a disproportionate role in the behavior of the PBAR, and sothey noted a strong preference to minimize changes to internal geometry and a requirement that the volume was to be kept the same as the original. The control volume was defined by the edges where the volume intersects with the roof of the machined cylinder just below the cavity. This body was exported separate for evaluation and for use later as construction geometry. The functional decomposition is presented in Figure **4-5**, The sub-features are denoted as characteristics and how they were expected to have been fabricated is the embodiment. The minimum wall thickness was measured but not included as a characteristic of this feature as generating the neccesary wall thickness was considered trivial when compared to difficulty in producing the negative space using AM.

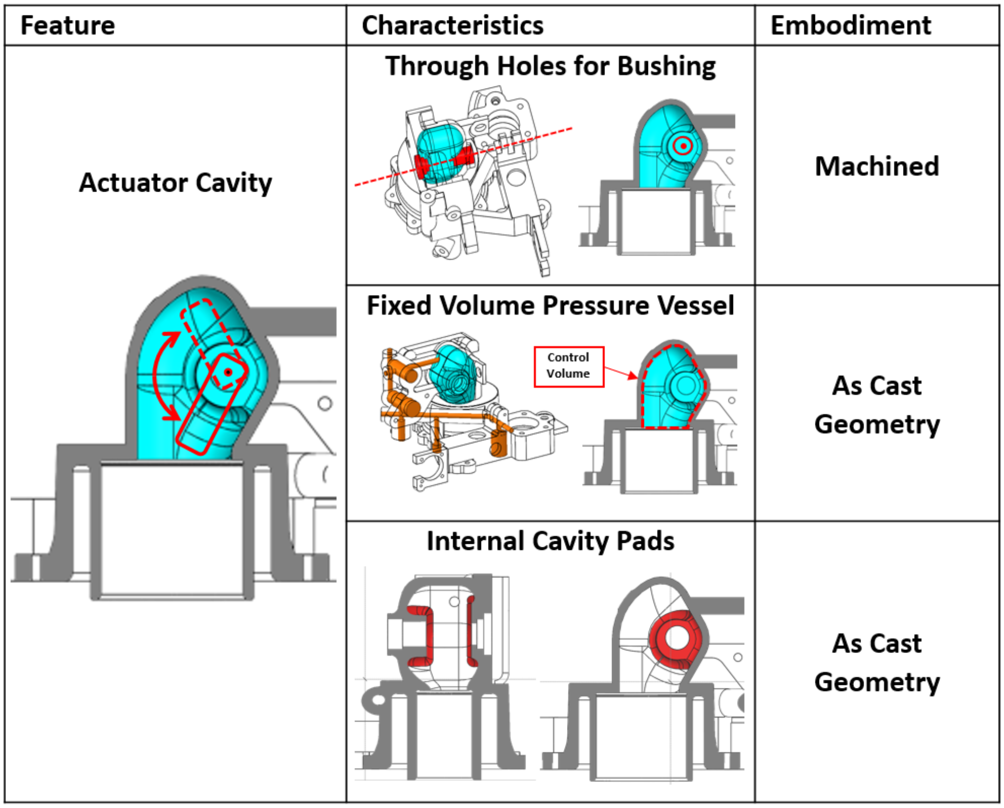


Figure **4-5**: Actuator Cavity functional decomposition showcasing the characteristics and the embodiment.

4.2.2. Functional Decomposition of the Internal Passages

The Internal Passages were the other predominate feature of concern, both as elected by the TA and FST, but also from a manufacturability standpoint. This network of passages is used to transport high-pressure / high-temperature air to various other subsystems connected to the housing. In the original article, these passages were generated by drilling the passage from multiple directions, with turns in the flow coinciding with where the drill points intersect. Unnecessary openings in these passages generated by the machining operation were threaded to recieve a plug that is cured in place, a process referred to as “machining and back-capping”. The full MPP expected to have been used to generate these passages on the original design is shown in Figure **4-6**.

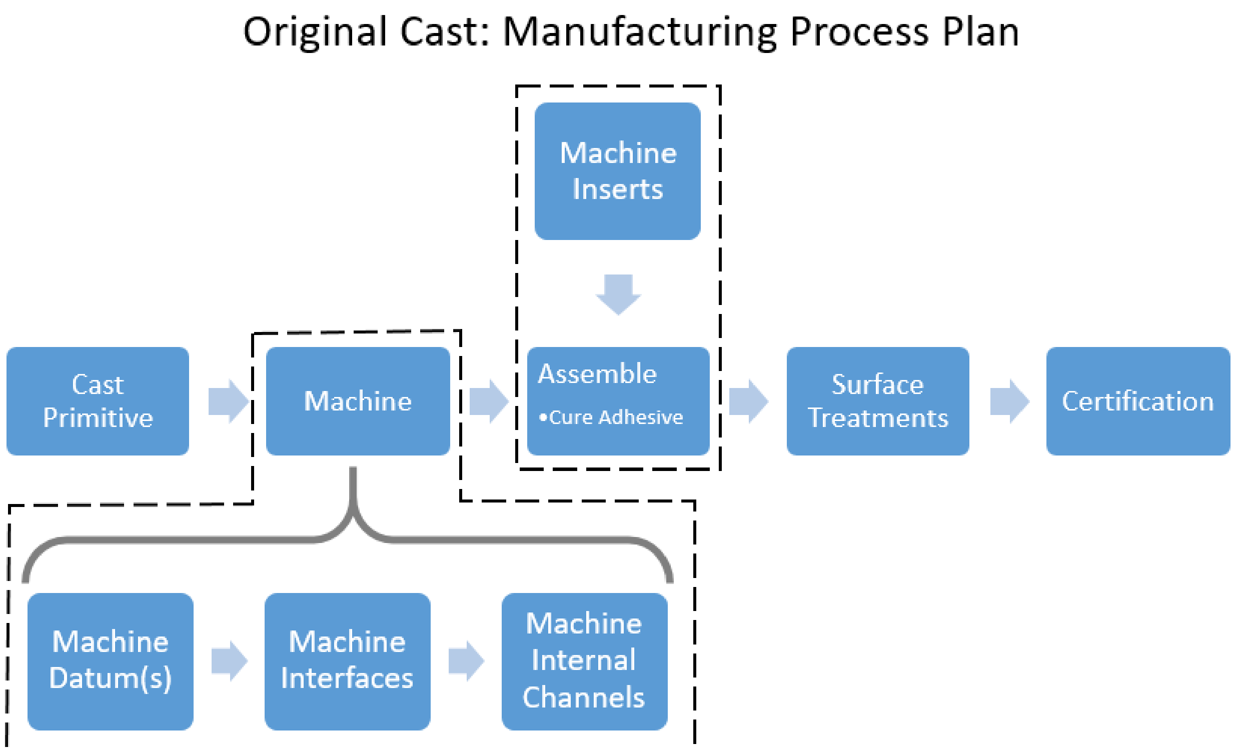


Figure **4-6**: MPP expected to have been used to generate the complex internal passages on the PBAR Housing, The back-capping is the assembly and curing of the inserts in the machined casting.

The TA and FST indicated that changes to the volume and path lengths of these passages could similarly have an undesirable effect on the operation of the systems, which relies strongly on a predictable distribution of the high pressure air. The orifices of the passages were predominantly machined faces and transitioned into the machined passages. One of the orifices was designed to receive a threaded component which was not provided, presumably to restrict the flow into that particular cavity. As these machined surfaces were expected to mate with the components with the same form and finish requirements, they were referred to as “Entry and Exit Ports” and considered to be one characteristic embodied through primary machining for the functional decomposition shown in Figure **4-7**.

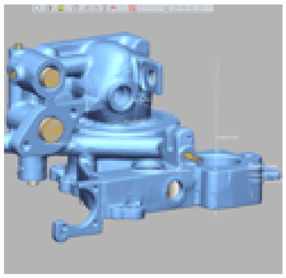
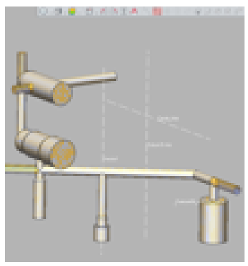
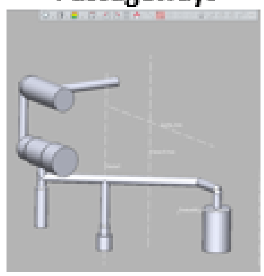
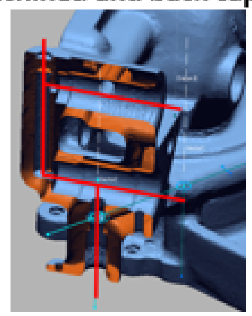
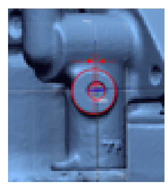
Feature	Characteristics	Embodiment
 Internal Passageways 	Entry and Exit Ports	Machined Or Threaded
	Through Pressure Passageways 	Machined and back capped 
	Wall Thickness 	As Cast Geometry • permitting Machining tolerance • Factor of Safety for pressure load

Figure **4-7**: The functional decomposition of the Internal Passageways, The mismatch is shown in the icon under Wall Thickness and the expected rationale behind the current state is listed under the embodiment.

Significant mismatch was noted between centerline of the bulk material of the passages and the centerline of the machined passage inside. Given the age of the original component, these passages were most likely generated on some purpose built fixture where primary machining occurred after some datum alignment. Bias in this alignment would result in a shift of machined geometry leading to the observed state of the casting surfaces used for alignment. To accommodate the alignment risk in the original component, the wall thickness would have needed to be increased proportional to any permissible shift, so that sufficient wall thickness would remain to tolerate the pressure the working fluid would impart during operation without rupturing. Armed with the knowledge that the article used to generate the CT scan was not pulled from the supply system for damage to this particular feature, the minimum wall thickness was found and noted as a possible limit to be used during the redesign.

This feature presented the most design freedom to recover margin for maintaining the center of mass and final mass during redesign on account of the excess material allocated to accommodate the original machining operation. The as-cast geometry used to generate a normal surface for the drilling operations was present as a functional requirement for the "machine and back-cap" MPP used on the original. Shown in Figure **4-7**, the desired passages on the original in shown in the icon under the "Through Pressure Passageways" Characteristic, the original designers were limited to by the MPP available to them and generated the geometry shown in "Internal Passages" under the Feature section.

Construction geometry for the passages was generated during the reverse engineering process. The diameter of passages was noted to coincide within 0.001" of a common imperial drill size and was thus used throughout for (re)design of the connecting passageways. All the "Entry and Exit Ports" were noted to be orthogonal to the assumed datum. As these interfaces mated with other components, the FST was asked to check the dimensions derived through the reverse engineering process against any available tech data for the next higher assembly, in lieu of a form fit test.

4.2.3. Functional Decomposition of Other Geometry

The negative space of the Actuator Cavity and Internal Passages was used to boolean-subtract from a parametrically modeled body of the rest of the housing. Machined faces were noted, but were not distinguishable from the as-cast surfaces of the body that was generated, see Figure **4-8**. Places where the housing was damaged were discussed at length with the FST to determine the expected geometry in these locations, with evidence gathered by looking at the next higher assembly and other PBAR housings still in-service. Not every draft or fillet from the original design was incorporated in this final part as the cost of incorporating them became higher along with net diminishing returns on the fidelity of the final mass and location of the center of mass.

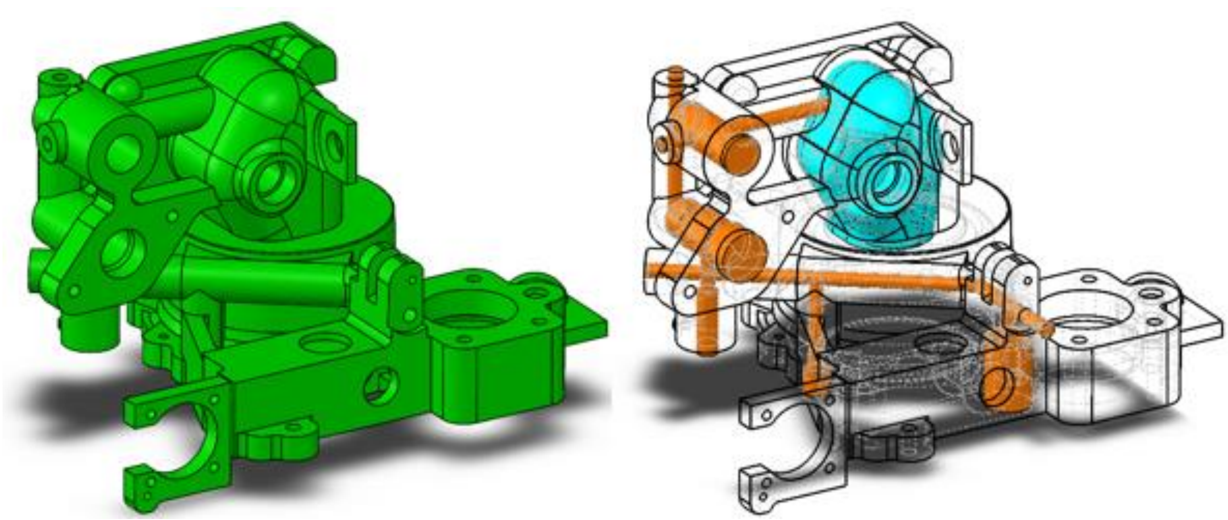


Figure **4-8**: The generated construction geometry from the reverse engineering process, Green is the Primary Geometry of the Housing, orange is the Internal Passageways, and blue is the Actuator Cavity.

The body was used in the aforementioned Autodesk Netfabb simulation to understand the impact of build orientation. The generation of this and the aforementioned construction geometry was initiated during the Discovery phase in response to the lack of product definition. The full process to generate these bodies lasted through till the end of the Concept Development phase. Much of the Functional Decomposition did not require the full product definition in order to extract the requirements used in identifying a coherent strategy for the design effort. This is important, as there may be a penchant for new practitioners to adhere to the letter of the DfAM+ framework, when the intent of the framework is to minimize the effort spent in converging on a viable MPP is the point.

4.3. Concept Development

Using the results from the Functional Decomposition, a series of MPP concepts should be generated to address any uncertainty in how to satisfy those requirements. Some characteristics or requirements may be self-evident in the required MPP to achieve them. Do note, this is also a time to negotiate and refine any requirements identified or declared up in to this point. Pre-conceived notions of the requirements and preferred MPP may be brought to the table by various stakeholders. During this stage, both the requirement and MPP is evaluated for feasibility and performance. For particularly arduous requirements it is important to present a spectrum of MPP that may not explicitly satisfy the stated requirement, so as to illustrate the relative cost or difficulty of that requirement to stakeholders. This phase is about performing trade studies and then using them to converge on a preferred strategy and document the descision rationale as agreed to by the stakeholders. The following sections illustrate the nuances of the Concept Development process, shown Figure **4-9**, that were performed to build consensus behind the final MPP.

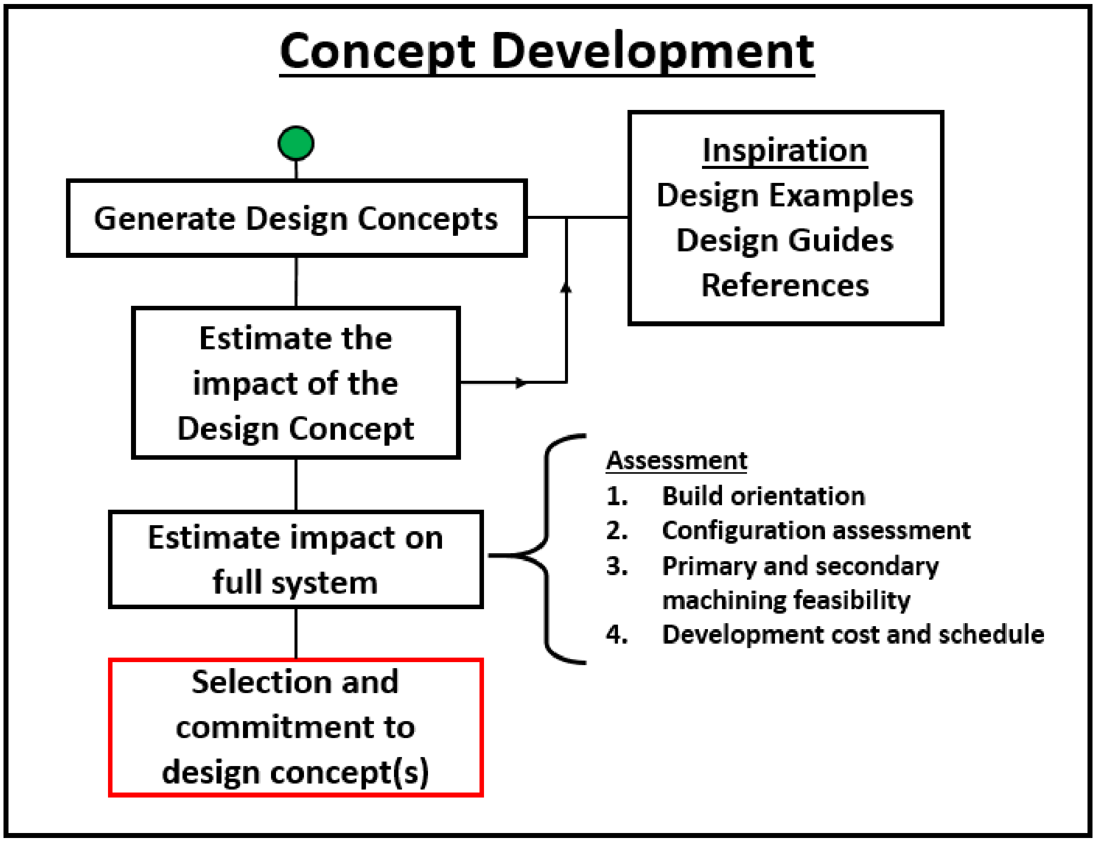


Figure **4-9**: The stages of the Concept Development phase of the DfAM+ Process

4.3.1. Concept Development of the Actuator Cavity

When NAVAIR selected this part as a candidate for this effort a concept for the MPP driven by the requirements of the Actuator Cavity was already favored by the TA. They proposed printing the PBAR in orientation 1, as shown in Figure **4-3**, and have solid support material inside the cavity to address the overhangs, to be removed through primary machining with a ball-nose end mill. After consulting with the Manufacturing personnel, they confirmed that the reach required to machine away the support material was likely to induce chatter. This would impart significant defects into the finished machined surface, or could break the tool. As such, the TA's initial MPP concept was deemed impractical.

The possibility of changing the geometry to make the cavity self-supporting in build orientation 1 was evaluated next. This would result in an alteration of the bounding box occupied by the PBAR by lengthening the actuator cavity in the build direction. This option was discussed with the FST and they took action to see if it would interfere with other parts in the aircraft. The FST determined that the risk of it interfering was sufficiently low that the option could remain on the table, but TA approval would be required as it ran counter to one of their directives.

A second orientation was evaluated as fewer modifications would be required for the inside surfaces of the actuator cavity. It presented the added benefits that it allowed for easier powder removal and that these surfaces would be "upskin", which is commonly associated with a better surface finish as compared to the "down-skin" surfaces generated in orientation 1. The disadvantages of using orientation 2 are illustrated in Figure **4-3**. The additional support material would require significantly more primary machining and would lead to increased distortion. Though not a particularly palatable choice, it had to be considered and weighed against the requirement to maintain the original shape as closely as possible.

4.3.2. Concept Development Internal Passageways

Initial discussions of options for the Internal Passageways centered on evaluating the opportunity cost of leveraging the complexity AM with primary and secondary machining processes. It was possible and relatively straightforward to employ the machine and back-cap strategy used on the original, but this option was considered an underutilization of AM. Using it would begin to beg the question, if PBF-LB/M is the appropriate technology for this application considering a Geometric Complexity was cited as part of the justification for this effort by the TA.

It is possible to print these complex passages in the manner demonstrated in Schmelzle et al. [6], and subsequently machine all the interfaces. This could leave a rougher texture which the TA and FST expressed concern that it could result in a significant increase in the head loss through the passages. Abrasive Flow Machining (AFM) was floated as a candidate secondary finishing process improve these passages, but the cost of implementation was not well understood at the time.

Existing design guides published by OEMs rarely discussed how best to leverage AM with other manufacturing processes [23-25]. If a subtractive process such as drilling was mentioned, it was with a reminder to undersize holes so they could be machined to final dimension. Primary machining concerns were often glossed over as offering a generic amount of machining stock to surfaces. They appear to be devoid of nuanced primary and secondary machining concerns, such as expected tolerances for locating a machining operation by working from the datums generated on printed surfaces verses locating local to the machining operation in question. They certainly do not cover classes of options for internal passages beyond some recommendations dependent on the cross-sectional area of the passage.

To aid in evaluating the design options, a trade study was conducted to evaluate the spectrum of MPP that could be used to cover the range of requirements for the Internal Passages. This ranged from the low tech solution of machine and back-cap intersecting channels all the way to various types of requirements which could be levied against complex printed passages finished with the AFM process. The trade study, see Figure **4-10**, is drafted to include the following:

- The driving requirements or options considered
- The high level MPP
- Expected relative difficulty in generating product definition
- Expected relative development and steady state production costs.
- Expected pros and cons for performance

Manufacturing Process Plan Trade Study: Internal Passageways with AM					
Option/Requirements	**Manufacturing Process Plan**	**Design "Costs"**	**Development "Costs"**	**Pros**	**Cons**
Straight Segment Passageways "Machine and Back Cap"	1. Print Net Shape 2. Heat Treat 3. Machine Internal Passageways and Interfaces 4. Machine Inserts 5. Install Inserts	• Low – Path + Diameter • Inserts for Back-Cap • Inspection Plan	• Machining Fixtures	• Quick Design • Quick Development • Minimal Inspection Costs	• More Material to be printed • Limitations of Path Complexity
Complex Passage • No AFM	1. Print Passage Net Shape 2. Remove Powder 3. Heat Treat 4. Machine Interfaces	• Complex Path • Complex Profile • Plan for Powder Removal	• Tooling? (minimal risk) • Certification Test Stand • Low risk of prototype loops	• Less Final Mass • Moderate Design Difficulty • Low Development Costs	• Passages have high skin friction • Chance of debris • Certification?
Complex Passage with AFM • Surface Profile Control • Surface Finish Control	1. Print Passage Net Shape 2. Remove Powder 3. Heat Treat 4. AFM 5. Machine Interfaces	• Complex Path • Complex Profile – Plan for Adjustments • Plan for Powder Removal • AFM Tooling • AFM Plan • Additional Material for AFM Profile Control	• Tooling • Certification Test Stand • High risk of prototype loops • AFM Tooling • AFM Process Development • Cost of Inspection for Each Prototype (CT, Destructive)	• Less Final Mass • Better Performance • Low risk of Debris	• High Risk of High Development Costs • Highest Cost of Inspection • Higher Cost to Outsource • Risk of Long Development Schedule • Cost of Final Certification • Process Documentation
Complex Passage with AFM • Performance Target Requirements	1. Print Passage Net Shape 2. Remove Powder 3. Heat Treat 4. AFM 5. Machine Interfaces	• Complex Path • Complex Profile – Plan for Adjustments • Plan for Powder Removal • AFM Tooling • AFM Plan • Additional Material for AFM Profile Control	• Tooling • Certification Test Stand • Moderate risk of prototype loops • AFM Tooling • AFM Process Development • Cost of Inspection for Each Prototype (Performance Based)	• Less Final Mass • Better Performance • Low risk of Debris • Direct Tolerancing of Performance Requirements	• Reasonable Risk of High Development Costs • Lower Cost of Inspection • Higher Cost to Outsource • Risk of Moderate Development Schedule • Cost of Final Certification • Process Documentation

Figure **4-10**: A table of the results of the MPP trade study conducted for internal passages

It was concluded the budgeted number of builds did not support leveraging the AFM process. If tasked with holding a tight surface finish and form error then there was a risk of a larger number of prototypes being required purely for dialing in the AFM process. If the form error was missed in the process of achieving the target surface finish requirements then a design change to the As-Built state of the part would be necessary. Considering the budget for the project only allowed for 1-2 failed prototype builds, and the AFM process development alone could reasonably be expected to consume more than that number. It might be a viable option if the intent was to mass-produce this component it as the development cost could be amortized across a larger number of units.

The machine and back-cap strategy was by far the easiest to design, comprising several points and directions to define the straight passages. It was noted to eat into the margins, since circular profiles require more material to make itself supporting as opposed the same cross-sectional area shaped in a diamond profile. This, coupled with the need to increase the wall thickens to accommodate primary machining margin in the location of the drilling process would eat into the margins for controlling the mass properties of the finished product. Without testing it would be difficult to determine which strategy would net greater head losses.

The impact of build orientation was not explicitly evaluated in this trade study. Nonetheless it is noted that orientation 2 would be easier for power removal, and orientation 1 can be accommodated by extending and turning the passages parallel to the bed.

4.3.3. Concept Selection

With the concepts generated by the Design Team in conjunction with the FST engineers, the TA was brought in to discuss and select a viable DfAM+ strategy to move forward with. As build orientation was driven by the Actuator Cavity, it became the focus of the debate with the TA and the FST. The concepts were presented as shown in Figure **4-11**. The most impactful decision was the DfAM strategy associated with the Fixed Volume Pressure Vessel characteristic, as this controlled orientation and orientation would set the strategy underpinning the Internal Cavity Pads.

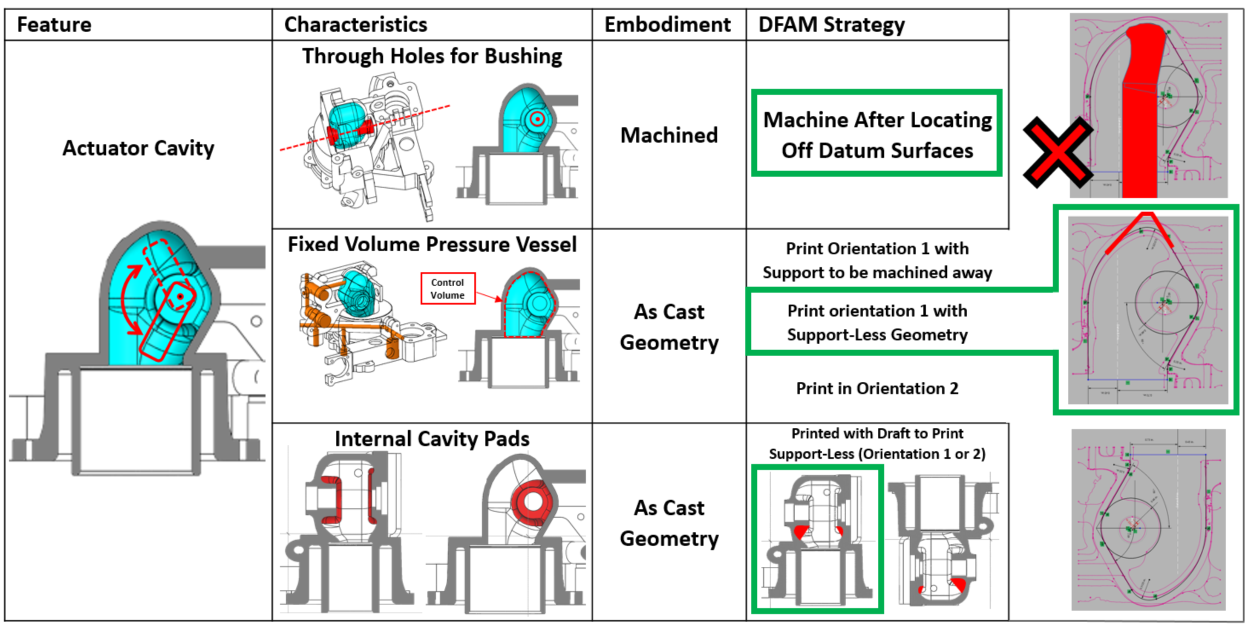


Figure **4-11**: The flow down from Feature, Characteristics, Embodiment, to DfAM Strategy for the Actuator Cavity showing the impractical concepts with a red “x” and the selected concepts in green.

Citing the issues confirmed by the Machinist, the TA’s initial concept was culled from the list with no pushback. This left the choice of build orientation between the two remaining concepts. The rationale behind choosing orientation 1 instead of orientation 2 was based on printability and reducing the required amount of machining operations. In orientation 1, the majority of the surfaces that would require support were ones that would have already required primary machining. In contrast, orientation 2 would have required machining stock on those surfaces and machining operations to remove all the blue supports shown in Figure **4-3**. The significant reduction in expected residual stress shown in Figure **4-3** implied a higher likelihood of the build succeeding. The risk of modifications interfering with the surrounding structure was determined to be sufficiently small in order to proceed. Therefore, permission from the TA was given to alter the geometry of the Actuator Cavity as long as the volume and size of the orifice was maintained to be consistent with the original.

Committing to orientation 1 enabled the focus to shift to a discussion of the Internal Passages concepts shown in Figure **4-12**. The conversation centered on the decision to directly print or fully machine the complex internal passages. Fully machining the complex passages was determined to excessively reduce the margins for maintaining the center of mass and final mass of the new design. Maintaining these mass requirement was already expected to consume a significant amount of design effort. Variations in complexity may be negligible for the producing the part through AM, but the time spent designing said complexity is anything but free. The smaller the margins are for hitting this requirement, the longer it would be expected to take to take to design to achieve them. Considering that the generative design tools are not well suited for the multi-objective problem of leveraging both AM and Primary Machining together to converge on a cost effective solution – the redesign effort must be manually performed. Reducing the design freedom by choosing a concept that reduces this margin could have a significant impact on cost and schedule. Alternatively, relaxing this requirement was expected to drive down developmental costs.

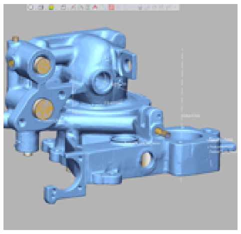
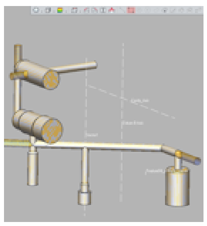
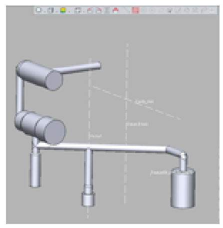
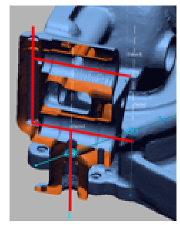
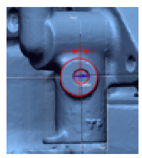
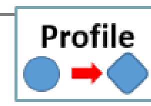
Feature	Characteristics	Embodiment	DFAM Strategy
 Internal Passageways 	Entry and Exit Ports	Machined Or Threaded	Machine or thread after locating off Datum Surfaces
	Through Pressure Passageways 	Machined and back capped 	Print excess thickness so as to machine and back cap as original
			Print to machine and back cap with printed pilot holes
			Print with diamond profile as to use as printed
	Wall Thickness 	As Cast Geometry • permitting Machining tolerance • Factor of Safety for pressure load	 Print with diamond profile with features to permit abrasive flow machining

Figure **4-12**: The flow down from Feature, Characteristics, Embodiment, to DfAM Strategy discussed for the Internal Passages.

The risk of having to relax the final part mass and inertia requirements was deemed by the TA to be less palatable than the alternative, and the decision to print self-supporting Internal Passageways was made. The discussion now centered on the expected surface roughness or risk of trapped powder inside these printed Complex Internal passages. Geometry to aid in powder removal could be incorporated by extending ports to more ready accessible regions. Any powder not removed would sinter to the walls during stress relief operations prior to Wire-EDM removal of the part from the build plate. This reduced the risk of leaving the internal passages unfinished. The final concept for the Internal Passages is illustrated in Figure **4-13**.

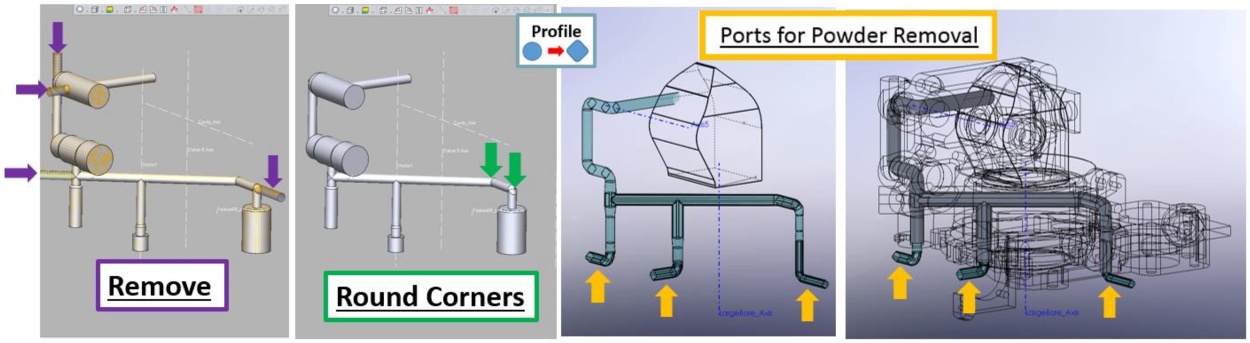


Figure **4-13**: The final concept agreed upon for the Complex Internal Passageways, from left to right, removing the entry lengths from "Machine and Back-Cap", Round sharp corners, Change cross-section to a self-supporting profile, add ports for build orientation 1 powder removal.

AFM was assessed as a means to smooth internal passages. The risk of incorporating a MPP to use AFM was the expected additional cost and schedule uncertainty required for process development. The TA rationale behind wanting to require AFM was scrutinized at length. The TA felt that providing a surface finish specification for the internal passages would eliminate the risk of excessive pressure head loss and debris in the system. Doing so, would have driven this large part to be inspected with a CT scan for finish and form error, or through destructive inspection if the part was manufactured at scale. The results from the trade study were leveraged at this time. The additional cost and impact on schedule was noted and explained to the TA as this risked having the design effort exceed the budget provided to CIMP-3D for this effort. There was no simulation backing the assumption that the surface finish cited would reliably achieve the desired target performance. The rationale behind the requirement stood predominantly on assumptions, not on testing or prior experience. The decision was made to complete this design effort without AFM. Test stand performance that would be used to certify the new design could be used to determine if AFM would be required. If necessary a follow-on effort could be quickly commissioned to modify the powder removal ports, seen in Figure **4-13**, to receive tooling for the AFM process and a target window for acceptable head loss could be used to drive the process development for AFM and an opportunity to allocate funding for that explicit effort.

The Tab pointed out in the Netfabb build simulation results in Figure **4-14** was determined by the FST to serve no verifiable purpose per review of the operating and maintance manuals for this system. Eliminating it would recover margin useful in maintaining the mass requirements and reduce the challenges associated with trying to retain this feature in the redesign. The TA recognized the benefits of removing the Tab and agreed that culling it was the right descision.

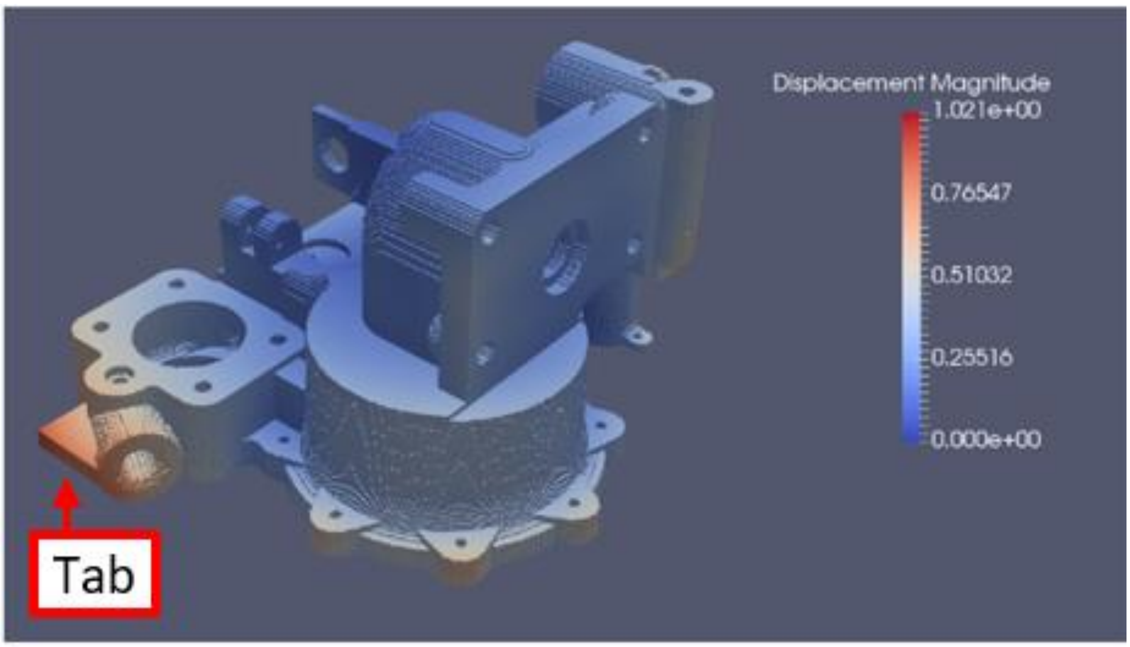


Figure **4-14**: Autodesk Netfabb simulation results for build Orientation 1, credited with raising questions that led to the removal of the Tab geometry for the redesign.

Before moving on to detail design, the topic of how to verify the redesign was a comparable drop-in replacement was discussed. Aside from all the mating geometry having the same GD&T requirements as the mating surfaces on the original, a satisfactory inspection method for checking the internal passages needed to be drafted. A proof load in a test cell is employed on the original to check for leaks and the risk of rupture. To check for debris, the running a working fluid such as water through these passages using a filter to check for particulates was a low-cost solution offered. The test could be rerun until the filter was free of debris, helpful in flushing away any chips produced during primary machining operations. The method, involving the creation of a small fixture and the drafting of a Local Process Specification (LPS), was rationalized to be more cost effective than CT scanning the housing to check for debris. The MPP for the agreed upon concepts is shown in Figure **4-15**.

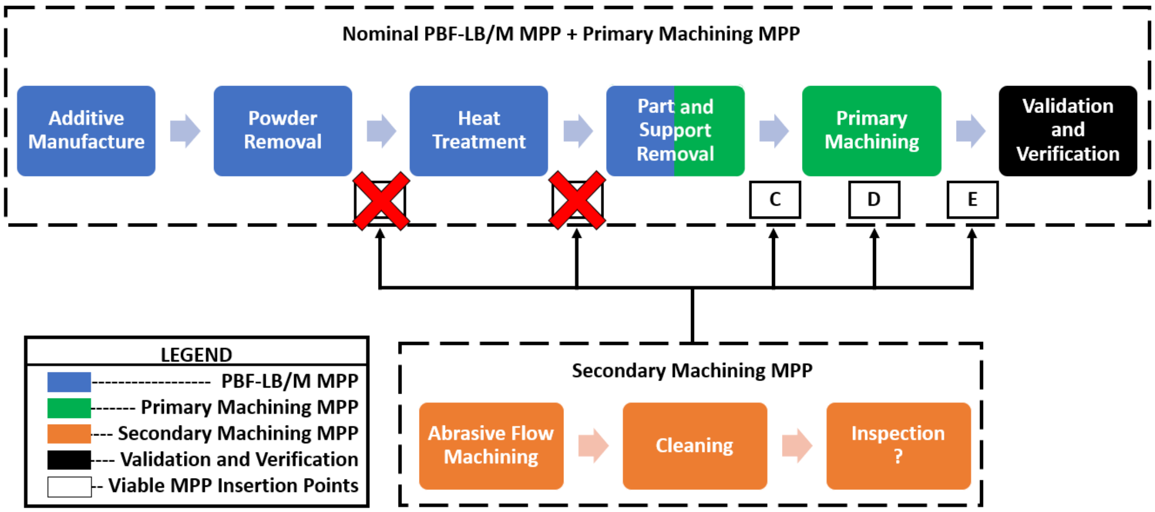


Figure **4-15**: The MPP for the agreed upon MPP concept with the contingency plan of incorporating the AFM MPP in one of the designated positions should it be deemed necessary to commission a follow up to the design effort based on test stand results.

With the buy-in from the TA on the DfAM+ concept the detail design work of modeling the new design could begin. A point of contact was designated from the FST to field questions that may arise during the next phases with them being empowered to raise any modifications to the requirements with the TA if warranted. The TA credited this method of evaluating the full MPP - including identifying methods for verification, during the concept development phase - with building their willingness to entertain leveraging AM in this application over prior DfAM efforts they had participated in.

4.4. DfAM+ Detail Design of the Final State

Armed with the agreed upon strategy for the down-selected features, the next task is to generate an acceptable final design for the PBAR housing. The DfAM+ process for generating the target final state outlined in Figure **4-16**, starts with the detail design of the aforementioned features and works towards incorporating them into a single body, useful in evaluating the intended final state.

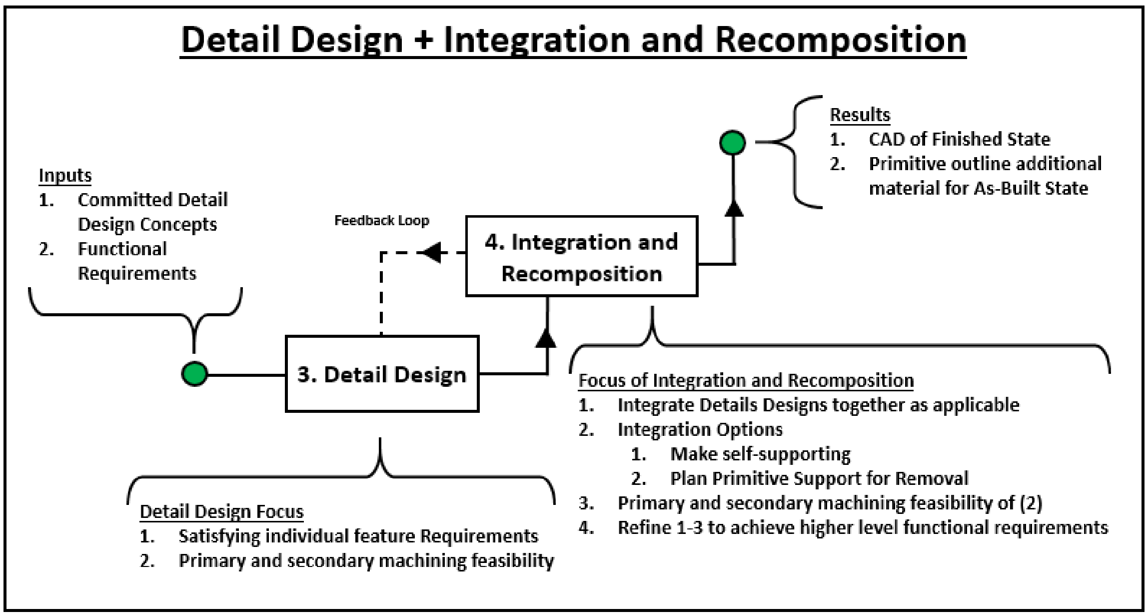


Figure **4-16**: Illustration of the Detail Design and Integration and Recomposition design phases

To aid in tracking manufacturing complexity and reducing the risk of overwhelming the design team, a practice of color coding bodies and surfaces was developed and implemented in the Solidworks CAD environment. The practice is outlined in Table **4-1** and illustrated in Figure **4-17**.

Table **4-1**: Color code and terminology for identifying geometry during the DfAM+ process

Modeling Color Type	Definition
Committed Material "grey"	• Material designated to satisfy an explicit functional requirement • Material whose form and function is "settled" or no longer subject to change • The designed or intended final state of the part after post processing
Uncommitted Material "blue"	• Material actively being designed or subject to change • Material used to make the part self-supporting • Material used to connect disparate elements • Material which "could" be subject to removal
TBR (To Be Removed) "red"	• Support material not intended to be on the final part • Material intended to be removed via machining • Additional material added to mitigate form error during secondary finishing processes i.e. polishing, Abrasive flow machining, electro chemical machining

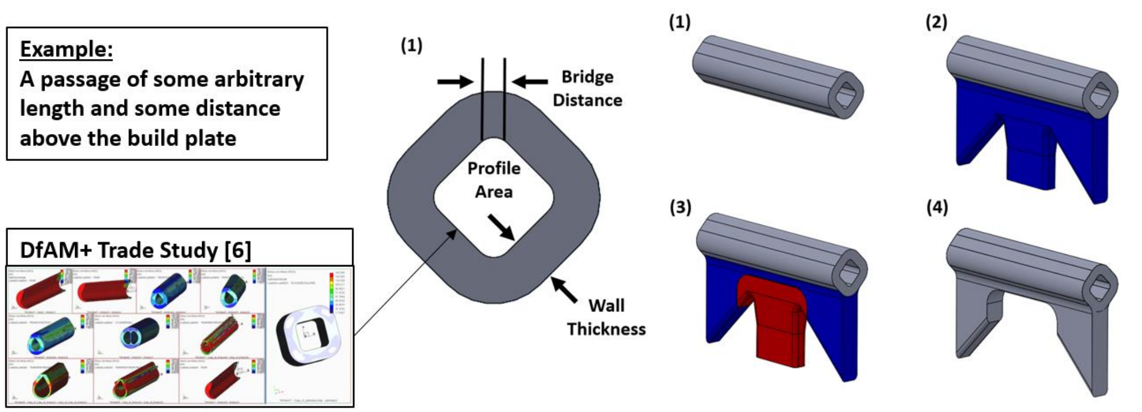


Figure **4-17**: Illustration of the modeling practice adopted in this case study, example is in-part based on a trade study on passage geometry from Schmelzle et.al [6].

This "best practice" is demonstrated in Figure **4-17**, using an imagined passageway to connect two bodies from some arbitrary feature in stage 1. The negative space of this passage is defined by some theoretical profile constrained by manufacturing limitations such as the bridging distance along the path from A to B. Based on the functional requirements of this passage, some thickness is defined and applied around this negative space. This body is referred to as

Committed Material because it is material designated to satisfy an explicit functional requirement. However, in this state it is not manufacture-able because there is no material to support this passage during the build process. A concept is generated to support this Committed Material during the build process, and is referred to as Uncommitted Material, shown in blue in stage 2 of Figure **4-17**. For final functionality, the middle section of this Uncommitted Material was determined to hinder the function of the final part, and must therefore be removed by machining. By keeping these bodies separate during the design process it is easier to discern if the material removal – shown in red as TBR or "To Be Removed" material - would interfere with the previously Committed Material. At this stage, the decision can be made to commit the previously Uncommitted Material to the intended final state of the part. The designed final state is shown as Committed Material in stage 4 of Figure 15. Note that the as-built state is a combination of the final Committed Material and the TBR material.

The boundaries of primary machining operations can be modeled as surfaces to respect requirements such as corner or fillet radius for a pocket cutting operation based on the geometry of the tool allocated to the operation. Reach of the tool can be incorporated to best approximate primary machining limitations such as accessibility. The surfaces can be used to generate the Uncommitted and TBR bodies through use of surface body operations such as the "Split" command in Solidworks.

The practice of color coding bodies and highlighting the region of interest when generating figures can facilitate clear and concise communication with the various stakeholders - especially machinists. It permits a shorthand method for designers to track primary machining complexity and perform an initial feasibility assessment for without entering into a Computer Aided Manufacturing (CAM) environment to generate toolpath. The Uncommitted material is helpful in focusing the stakeholders on the detail actively being worked on seeing where design freedom may be.

4.4.1. Detail Design of the Actuator Cavity

The concept selection started with the most impactful feature which is also a perfect place to start with the Detail Design phase. By starting with the most challenging features any issues in the DfAM+ concept can be found and addressed early, before significant effort is expended.

The detail design effort for the negative space inside the Actuator Cavity was reduced due to the time spent parametrically modeling the original cavity in Geomagic Design X. Aside from the surfaces of the Internal Cavity Pads that interfaced with the actuating arm there was a fair bit of air gap in the housing. As there would be negative space moved to above arc of the actuator to make the cavity self-supporting, this negative space had to be accounted for. It was expected that the gap opposite the arc of movement could be reduced by adding the material. The majority of the negative space would come from drafting the Actuator Cavity Pads. A strategy was devised wherein certain walls would be incrementally adjusted without effecting the motion of the arm until the volumes were approximately the same as the original, as shown in Figure **4-18**. The rough outline of the detail modeling strategy took less than an hour to draft and run by the FST POC. The primary construction geometry adjusted for this body is the two cross-sections illustrated in Figure **4-18**.

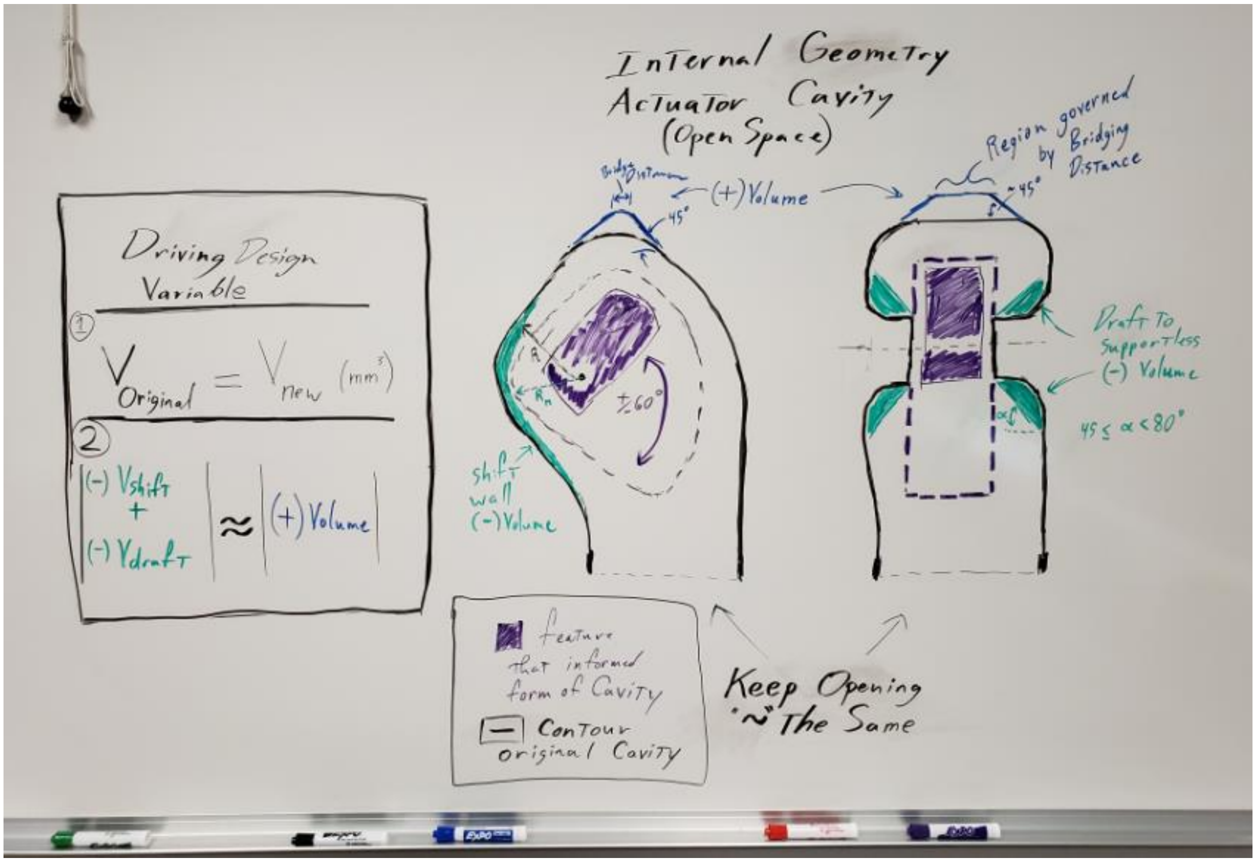


Figure **4-18**: A whiteboard mockup of the modeling strategy for achieving changing the shape while maintaining the volume during the detail design phase.

The increase in complexity made the fillet operations used to make the pressure vessel smooth on the inside prone to breaking in Solidworks. After significant effort, the DfAM actuator cavity overshot the target volume by approximately four percent of the original volume. After discussing this with the SME on the NAVAIR side, the deviation was considered acceptably small. The results of this work are showcased in Figure **4-19**.

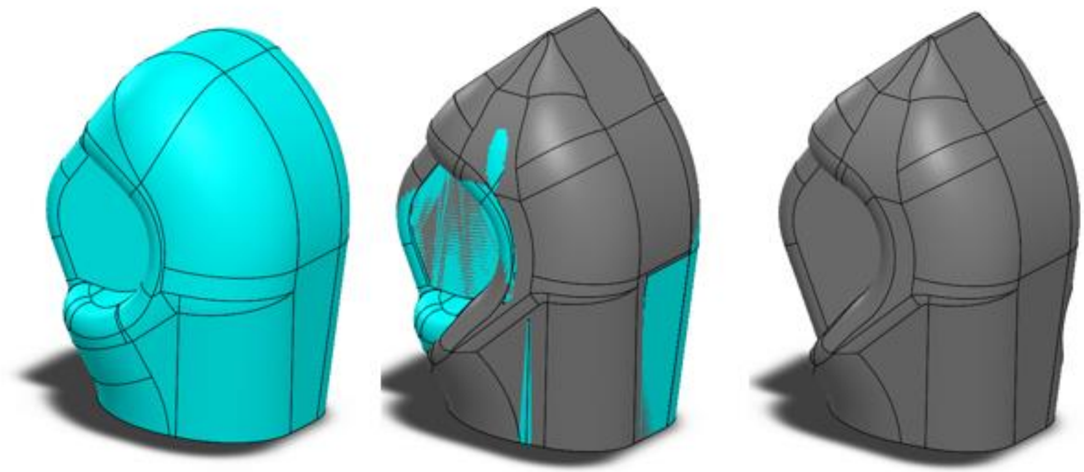


Figure **4-19**: Redesign of the internal volume of the Actuator Cavity. Left - Original Geometry, Right - Modified Geometry, Middle - Both shown overlapped. Blue - the original, grey - the new internal volume. Overlap shown in the middle illustrates the subtle change in volume, drawing attention to modifications to the top geometry that initiated this change.

The external surface geometry of the Actuator Cavity was modeled to be as close to the original as possible, where the cavity was made self-supporting the wall thickness used on the original was maintained along the new surface, only marginally thickening around the sharper corners by using a less aggressive fillet than that produced through a surface offset. This change in thickness was justified with the FST and TA by citing material property testing for the PBF-LB/M material and processing parameters evaluated with witness coupons from a prior research effort. The results showed that the properties the substituted aluminum alloy was better than the original cast alloy, and provide confidence that maintaining the same minimum wall thickness while changing to a better material maintained or improved the original factor of safety.

4.4.2. Detail Design of the Internal Passageways

Continuing with the next most challenging feature, the negative space of the Internal Passageways was modeled. From the construction geometry imported from Geomagic DesignX, wireframe paths were extracted along with the geometry for the primary machined interfaces. Considering the MPP intended powder removal prior to machining the negative space of the As-Built state of the passage was planned to include pilot holes below the diameter of the final machined state but greater than the size required to permit removal of powder. This was accomplished by transitioning from the self-supporting diamond profile, borrowed from Schmelzle et al. [6], to a cylinder that resembled a pilot hole over the length of the feature, as illustrated in Figure **4-20**.

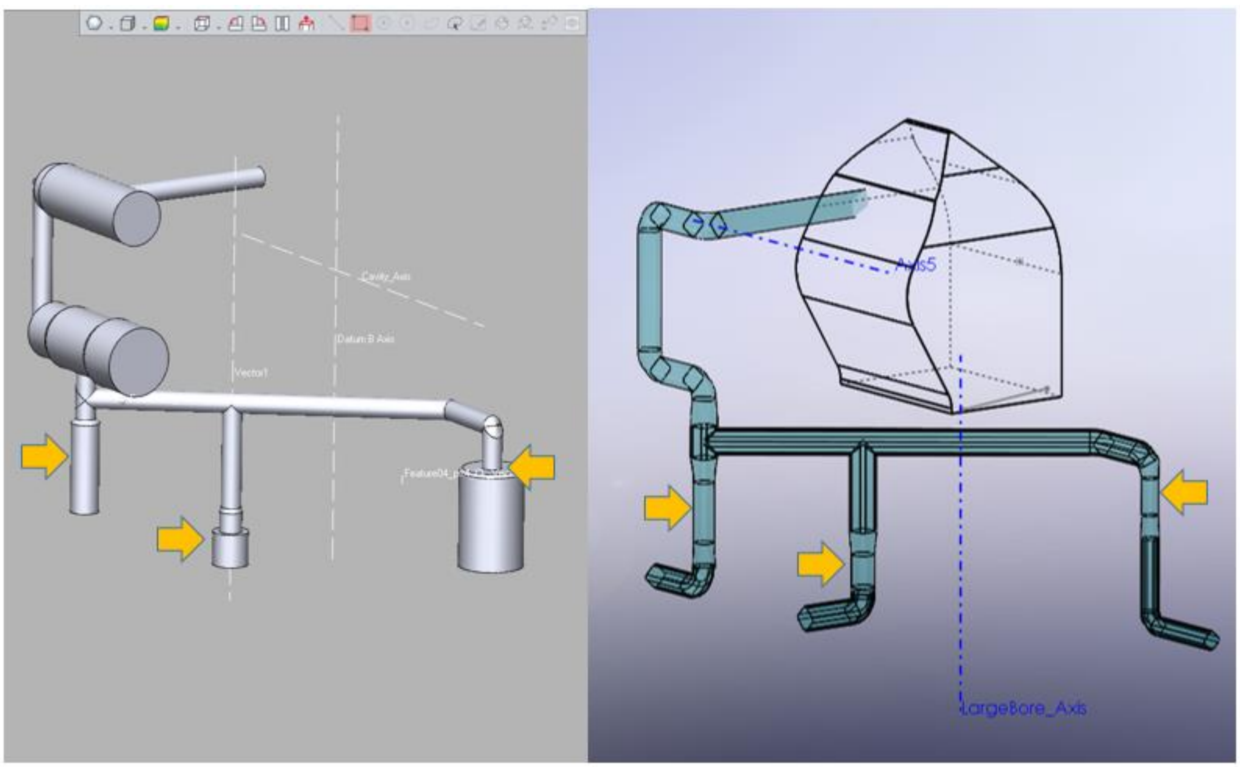


Figure **4-20**: Illustration of transitioning the diamond self-supporting profile to a pilot geometry for the As-Built state where a machined interface would be required.

Doing so allowed for any drill point of the primary machining operations to create a relatively simple transition from the machined profile to the printed complex passage. The machining operations could be defined from a datum alignment by touching off on datum surfaces or indicated local to the printed pilot hole if a sufficiently small probe was available to the machinist. The benefit of this forethought is evident in a section view, see Figure **4-21,** of a drilled and tapped interface on the finished design where the two machining operations are color coded.

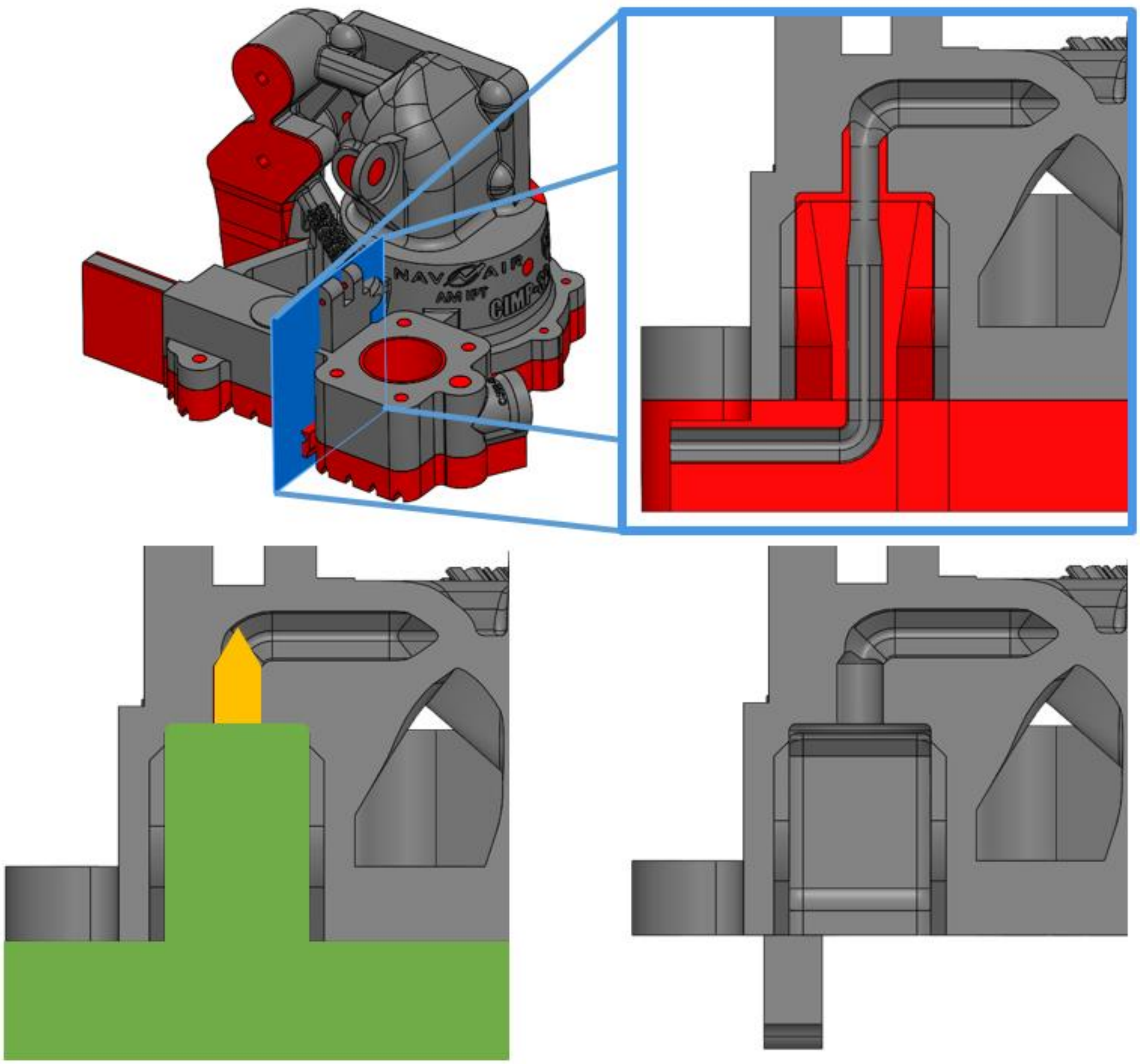


Figure **4-21**: A section-view of a later stage in the design showcasing the forethought in planning the primary machining operations when conceptualizing the As-Built state of the part. Grey is committed Final State, Red is TBR solid Support Material, Green is the outline of material removed with an end-mill, yellow shows the drilling operation with planned drill point for a geometry that is drill and tapped.

The minimum wall thickness along the Complex Passageway was set to be greater than the minimum wall thickness noted on the original during the reverse engineering process. This was again justified to the TA and FST through the material arguments used in support of the wall thickness on the Actuator Cavity.

4.4.3. Integration and Recomposition Towards the Final State

After the critical features had been modeled and verified to meet the feature specific requirements, the rest of the less troublesome geometry was modeled and as practical incorporated into a single Committed or Final State body. To permit for minor adjustments of the details where they don't easily mesh, the process has a tight feedback loop with the Detail Design phase as illustrated in Figure **4-16**.

As the Details started coming together, different concepts to make the committed material self-supporting were evaluated. Multiple variations of the Uncommitted material would be generated to minimize the amount of additional material, often drafting to the nearest face or in whichever direction netted the least amount of material. Examples of where this material was incorporated can be seen in Figure **4-22.** Note that not everything has TBR material for machining operations, except where the current Uncommitted material has TBR and primary machining operation planned.

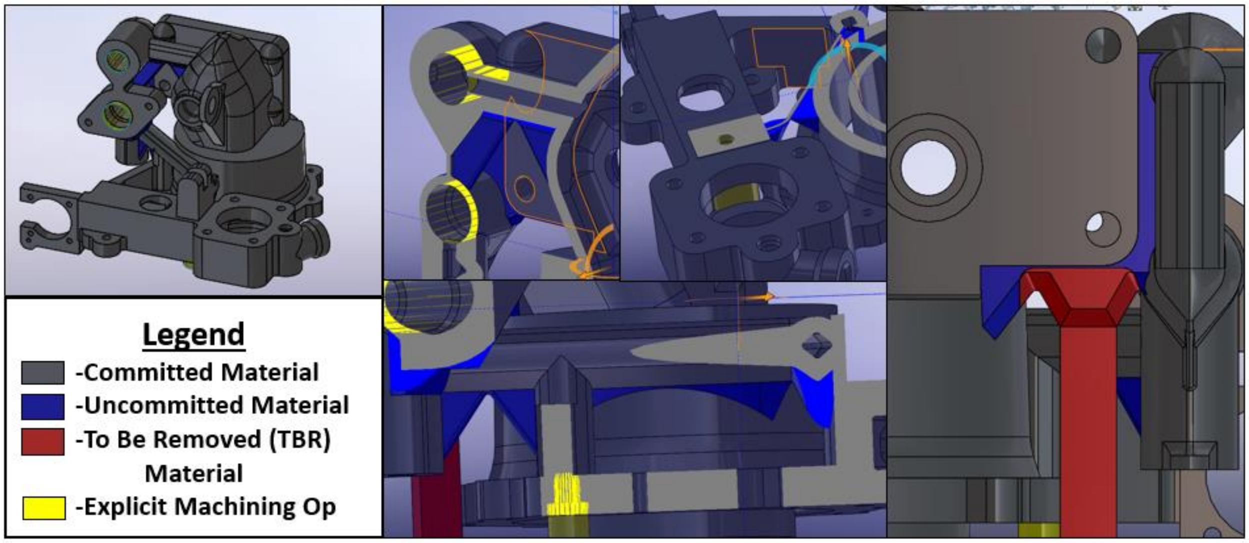


Figure **4-22**: A figure of the Uncommitted and TBR material that was adjusted during the final stage of the Recomposition phase to achieve the center of mass and final mass requirements of the final machined state of the part.

Due to the margins recovered as a result of the concepts selected, it was possible to achieve the center of mass and final mass requirements dictated by the TA by iteratively adjusting the Uncommitted and TBR material shown in Figure **4-22**. The center of mass and final mass were evaluated by temporarily combining the Committed and Uncommitted material together with a Boolean Union and evaluating it using the mass properties tool. Only the one TBR location needed to be adjusted to walk the center of mass to within a millimeter of the original location extracted from the reverse engineered model which kept the time spent adjusting down to only a 1-2 days. After achieving a design that had a center of mass location within 1 mm of the original, and a mass under a gram less than the original, the design was deemed “finished” and ready for final review. In the end the TA and FST concurred and wrote off the deviation as acceptable for the purposes of this effort.

4.5. Refinement and Prototyping

With the goal of adding and modifying TBR material to add primary machining stock, additional avenues for power removal, and refinement of the support structure to get it ready for printing the Uncommitted material was combined with the Committed material to form the basic product definition for the finished machined state. The final machined state was protected from editing unless there was an issue that necessitated additional adjustment. After the necessary solid support structure was drafted to the build plate, adjustments were made for powder removal considerations.

4.5.1. Issues with Powder Removal Geometry

Self-supporting arches were cut from one side of the support structure to the other to create a path for powder removal, connected to the Actuator Cavity. An unintended consequence of this strategy was the generation of Islands and Overhangs which could have induced a build failure. Islands do not connect to the build plate but instead rest of the bed of powder. Overhangs are unsupported geometry projected in a manner that risks significant distortion. An illustrated definition of Islands and Overhands adopted from the ISO standard on design recommendations for PBR-LB/M is shown in Figure **4-23** [30].

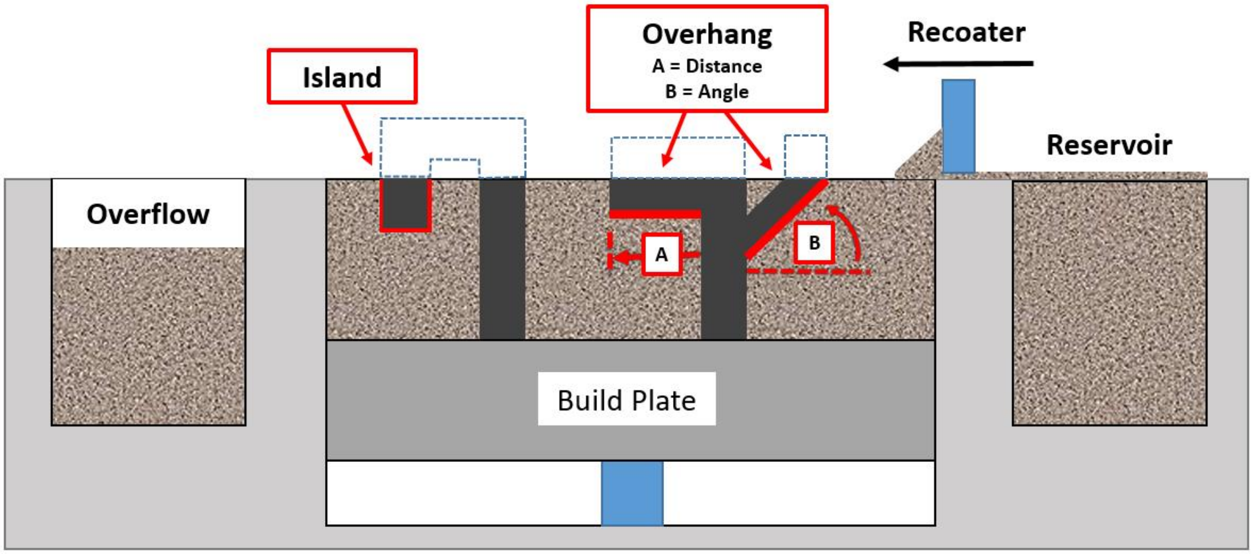


Figure **4-23**: Islands and Overhangs as illustrated in a PBR-LB/M system.

Both Islands and Overhangs can risk the success of the build. Islands, because they rest on a bed of powder, are not anchored to the build plate, and thus are likely to be swept up by the recoating operation. They can be swept into the overflow bin or if they catch on some other part of the build or machine they can pin themselves and damage the recoated edge or stop the build. Overhangs present a risk of distorting and either damaging the recoater or stopping the process entirely. Small distances or certain angles are considered safe to build overhangs. The hard and fast rule is the 45 degree self-supporting angle. Any angle more acute than that runs the risk of poor downskin surface texture and possible build failure. Both Islands and Overhangs were generated by the Arch geometry due to the intersection with various edges of the TBR material, shown in Figure **4-24**.

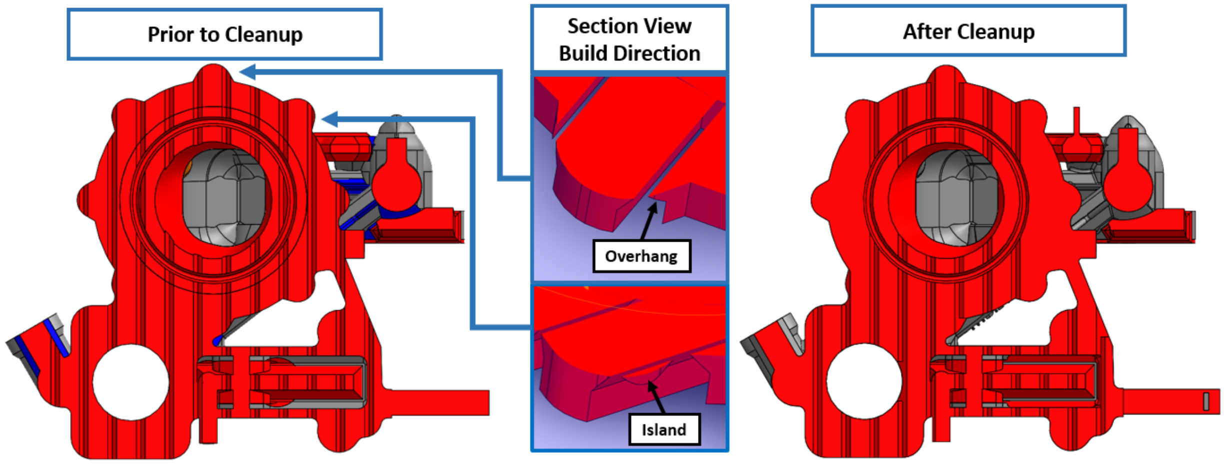


Figure **4-24**: Islands and Overhangs generated by the arch geometry, modifications were made to generate a workable state shown right.

These Islands and overhangs were discovered using the section view tool in the build direction, with a translation increment consistent with the intended layer height.

Both faces of these overhangs would register as self-supporting, the intersecting edge would not fall into the same category, it is this edge that presents the issue. Magics build prep software doesn't catch this kind of defective geometry because it evaluates overhang angles by evaluating surfaces and not their accompanying edges. The overhangs pointed in the direction of the recoater were especially concerning and needed to be addressed. Material was removed or the tunnel formed by the arch was filled in to fix these geometry defects. It required roughly one working day to find and fix these geometric defects. In hindsight, indiscriminately cutting channels from one side to the other of the support material was a poor decision. A more judicious selection of location of these openings for powder to escape would have saved significant time and effort.

4.5.2. Machinist Feedback on TBR Material

Illustrations were provided to machinists for final input on the TBR material, shown in Figure **4-25**. The machinist noted the geometry around the Datum B Axis. The cylindrical surface collinear with Datum B was approximately 1/3 of an inch. As the machinists were intending to probe datum B to indicate the coordinate system for the machining, any axis generated from this sliver of a surface could be inconsistent. They requested to make the cylinder taller so that a more accurate datum could be extracted. The modification was trivial and made the machinist's job significantly less difficult.

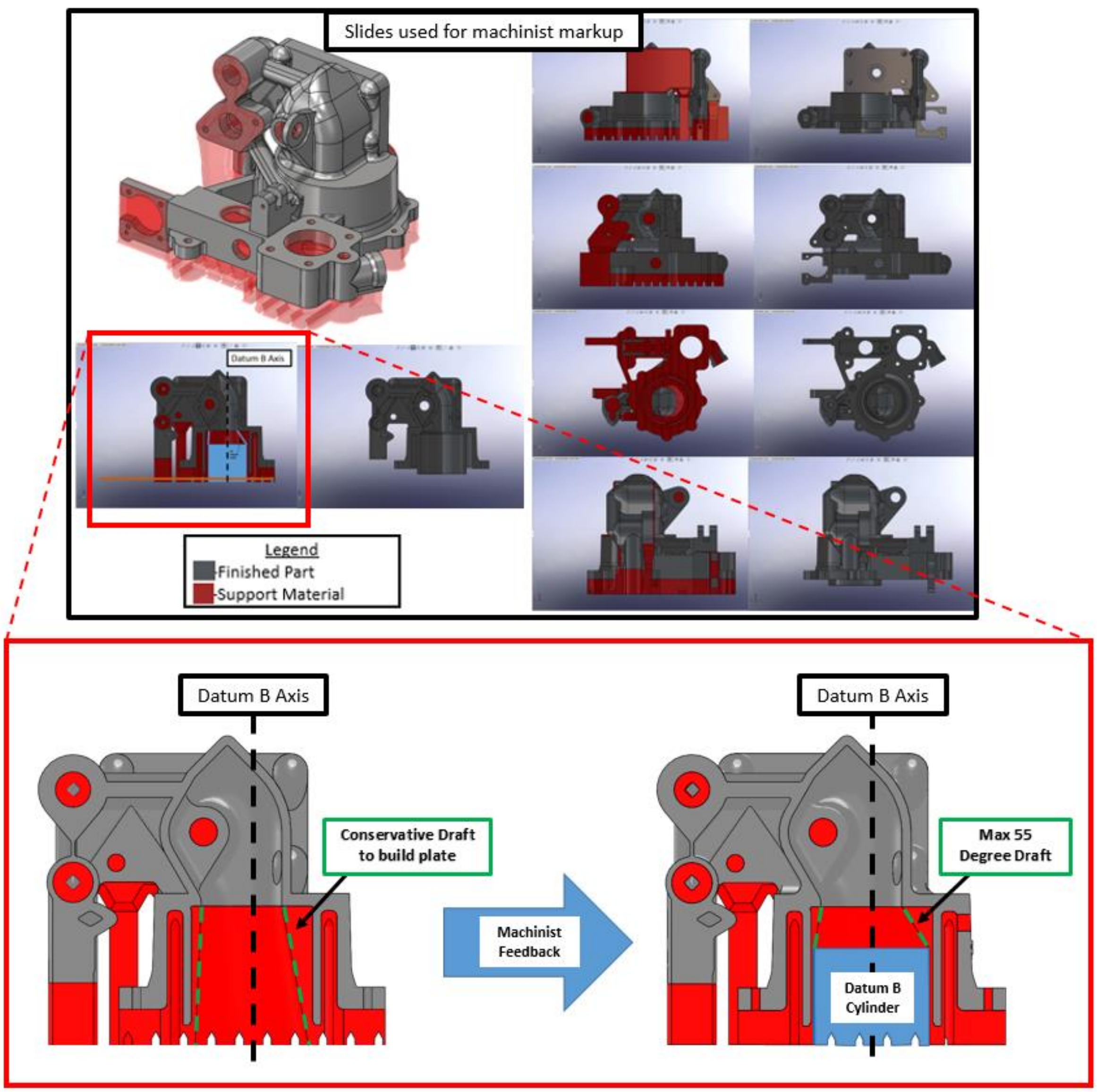


Figure **4-25**: Slides provided showing the TBR and Final Part side by side provided to the machinist for markup, the geometry change made per machinist feedback shown below.

After the feedback was incorporated the Final Machined state was combined with the TBR material to generate the As-Build state of the part used for generating CAM and AM toolpath. Both models would be provided to the machinist so they can work on generating fixtures for workholding and start generating toolpath.

4.5.3. Build Planning and Witness Coupons

The As-Built state is arranged in either in the CAD suite or in the build preparation software such as Magics or 3DExpert, along with any accompanying witness coupons added to assess build quality. Arranging in the CAD suite permits explicit location of the part and witness coupons relative to eachother prior to importing into the build preparation software. This reduces the effort required in applying toolpaths as these build preparation suites may not possess tools to exactly locate the witness coupons relative to the part in a time effective manner.

Witness coupons and the PBAR were arranged for this project in Solidworks, as shown in Figure **4-26**. Care was taken to provide easy access for tools to the powder access ports. The large overhang feature was pointed away from the recoater. Large flat faces of both the PBAR and witness coupons were canted five degrees relative to the recoater. There is always a risk of the recoater grazing the top skin of the part. The angle was introduced to stop from part from interacting with the recoater all at once in order to reduce the impulse force induced by any interactions between the part and the recoater.

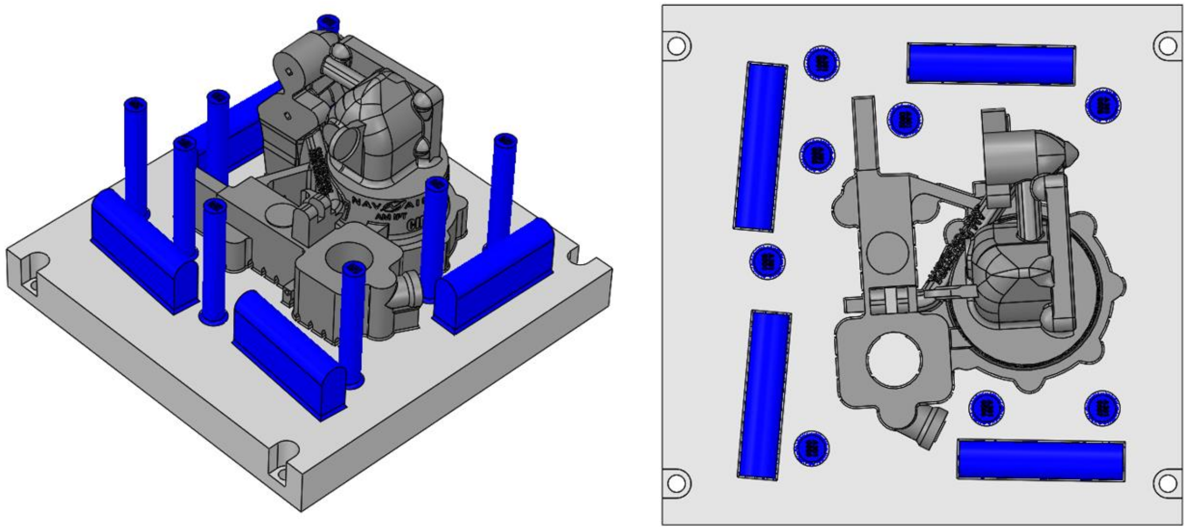


Figure **4-26**: Solidworks layout of the part (Dark Grey) on the build plate (Light Grey), Witness coupons (Blue). In the top view, shown right, the recoater would translate left from the right side of the build plate.

4.5.4. The Importance of Prototyping

Prototyping or the production of a first article allows for verification of the design beyond what simulations or best practices afford. Even when adhering to such commonly accepted DfAM rules as the 45 degree support-less overhang failure can still find a way. This was the case for the first prototype build of the PBAR, See Figure **4-27**.

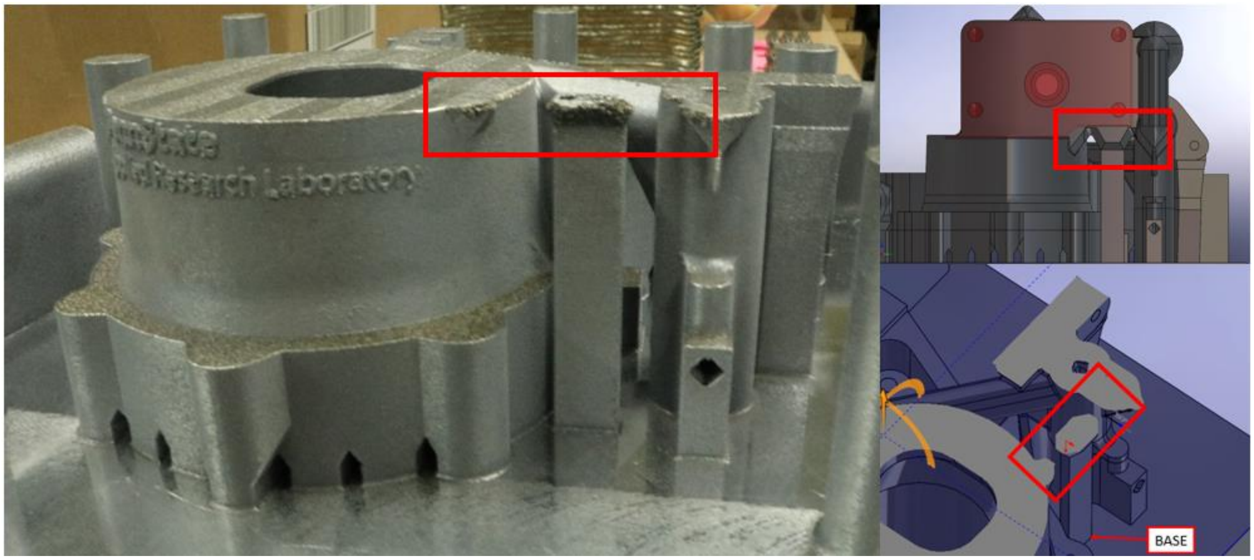


Figure **4-27**: The build failure which necessitated a redesign of the support material. The base was 3 mm x 10 mm which flowered out at a 45 degree angle to anchor a large block of material several inches from the build plate.

This geometry adhered to the support-less angle and still induced an error which damaged the recoater and ultimately caused the build to fail by stopping the recoater. After inspection, the tall aspect ratio of the base was suspected to provide inadiquate resistance to deflection when interacting with the recoater, possibly kicking up powder causing it to overbuild. The fact that the overhang was in the direction of the recoater certainly didn’t help.

The afflicting geometry was TBR material so adjustments could be made to it without requiring additional TA review, as this geometry change was unlikely to alter the final state of the part. The base was altered to be stiffer and present a gradual ramp instead of the 45 degree overhang in the direction of the recoater, see figure **4-28**.

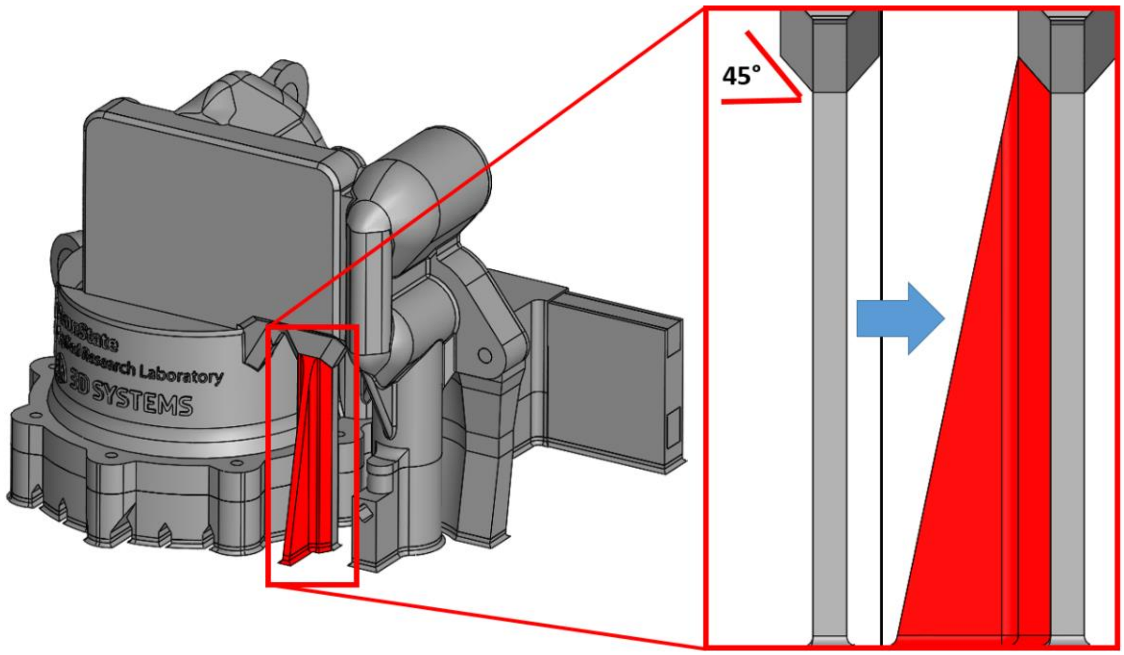


Figure **4-28**: The offending geometry was altered from the thin base with the 45 degree overhang to a more conservative geometry with a ramp shown right.

After these alterations, the buildplan enabled successful production of a prototype using the EOS M280. Subsequent builds were produced using both the EOS M280 and the 3DSystems ProX 320. The successful build is shown in Figure **4-29** alongside screenshots of the product definition with the TBR material made transparent. After powder removal and heat treatment the build plates with parts attached were shipped to NAVAIR for Wire-EDM removal from the build plate. The wire EDM was designated to be a planar cut, 2 mm measured normal to the build plate, thereby removing Matheck fillets from the PBAR, see the orange material shown left in Figure **4-29**.

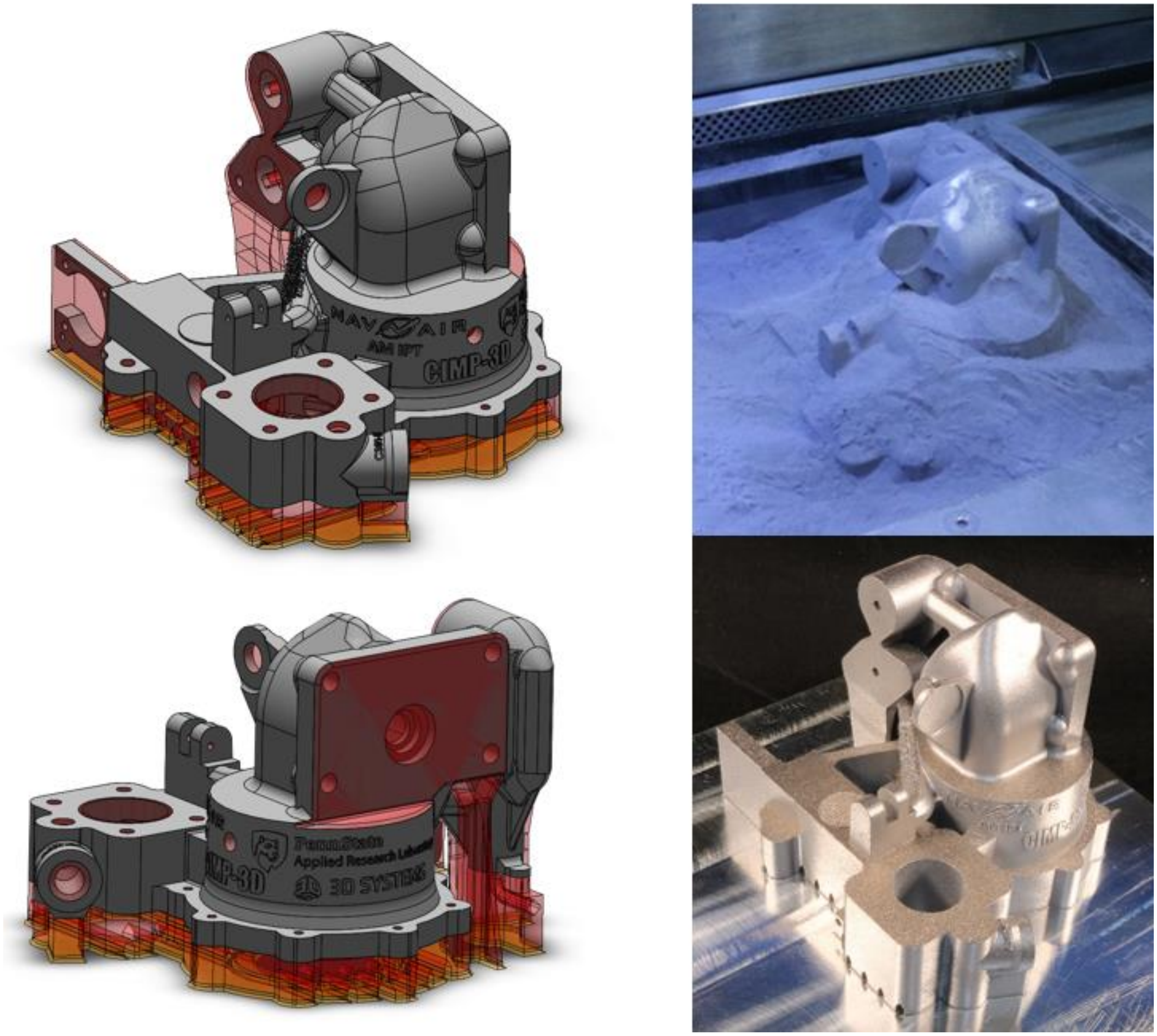


Figure **4-29**: Left the digital model of the produced PBAR, grey is the Committed final part geometry, red is TBR solid support material, orange at the bottom is the 2mm removed during wire EDM process. Top right shows the part in the EOS during powder removal, bottom right shows the part after powder removal

NAVAIR evaluated the prototype and determined that the quality of the downskin surfaces within the actuator cavity was consistent and substantially similar in appearance to the surfaces of the original. A picture from the moment after separating the PBF-LB/M PBAR housing from the build plate is shown in Figure **4-30**.

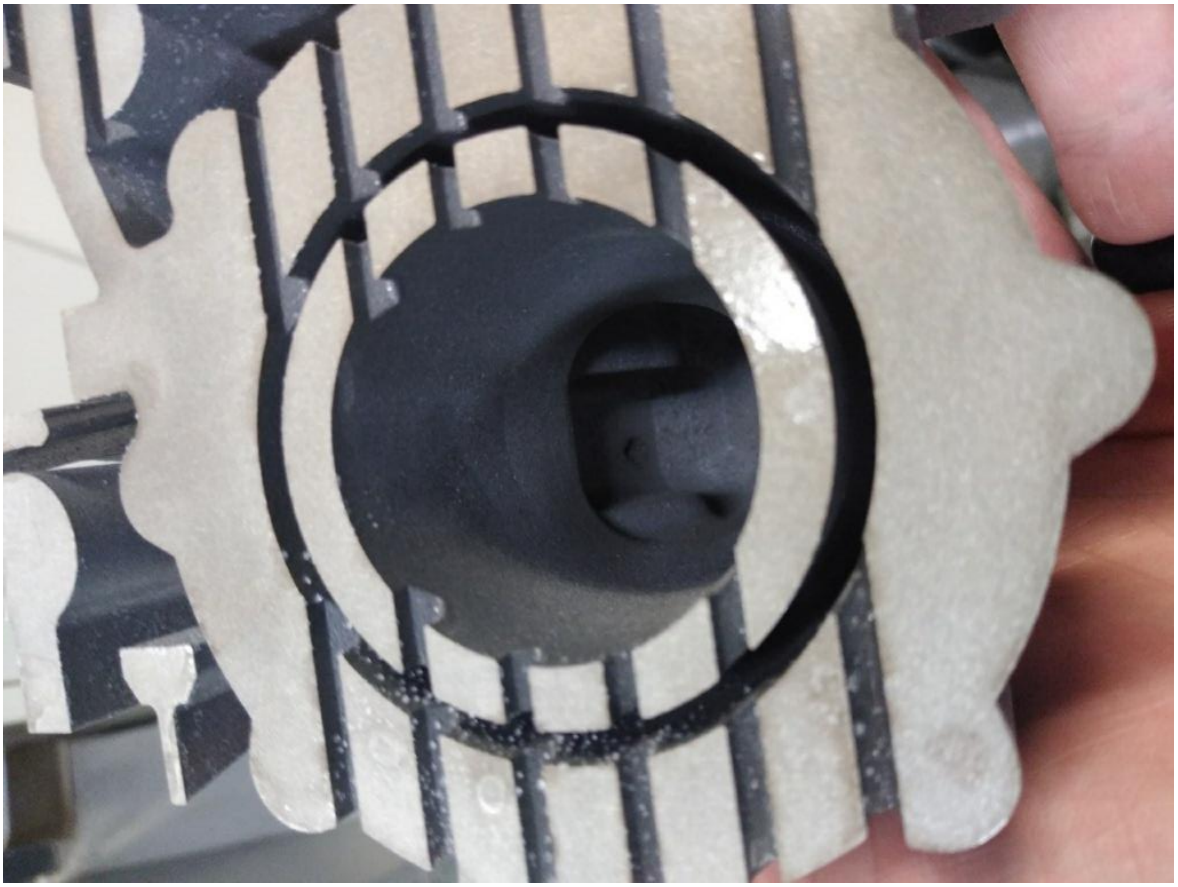


Figure **4-30**: The negative space of the actuator cavity revealed after wire-edm. Credit NAVAIR

The rest of the prototyping effort to include primary machining, was paused at this point due to lack of funds to enable NAVAIR to create tooling at take this part to the point it can be evaluated on a test stand. If the verification and validation are successful, then this part could be inducted into the supply system with the TA's direction. There are ongoing efforts to complete this work and induct it into a PLM environment for final sign-off and revision control.

4.6. Lessons Learned

This effort challenged the conventional thinking behind DfAM. Considerations for primary and secondary machining played a significant role in the success of this effort. While prior design frameworks discussed the process of design in the abstract, this work highlights an opportunity for academia to develop less abstract frameworks which are more nuanced for particular industries or applications. The following sections will highlight some direct insights generated during the course of this case study.

4.6.1. Stakeholder Contributions

The DfAM+ framework can be leveraged by a standalone user but is most applicable to a diverse team of stakeholders. Each stakeholder has a roll to play during different stages of the design effort. The question of how much effort is required with these stakeholders has not previously been studied in depth. In general, the TA may choose to be hands off – opting to course-correct after a prototype has been generated or rather may choose to dictate nearly every design decision. Either extreme can be problematic, but where to strike that balance warrants debate when it comes to designing solutions intended to leverage AM technologies. This work was able to document the approximate contribution of the various stakeholders in the form of a Gantt chart, see Figure **4-31**. Such breakdown can help provide estimates of required effort, thereby informing decision makers early in the process.

Phase 0 **Discovery**	1. Identification of the Part/Problem 2. Initial Assessment of the Part a. What Manufacturing Tech is feasible b. Estimate through Phase 2 – Based On i. Available Tech Data ii. Priority c. Questions about the Project 3. Build the Case for the Project 4. Make the case, Is this something the TA is willing to get behind 5. Tech Authority Blessing to entertain the Idea? a. If Yes => Continue to Phase 1 b. If No => Rejected
Phase 1 **Functional Decomposition**	6. Gathering/assessment of the current state of the part a. Collection of the complete product definition (MBD, Drawings, Hybrid, Reverse Engineering) b. Critical characteristics of the component (Loads, etc...) c. FST collection of Production issues along with recommendations 7. General Functional Decomposition 8. Ranking Features a. Importance for the function of the component 9. Down Select Features a. Difficulty b. Downstream Impact
Phase 2 **Concept Development**	10. Generate Design Concepts for each feature 11. Estimate the impact for each concept a. Non-Recurring Process development Costs b. Full-rate production cost c. Non-Recurring Design Costs d. Cost of Qualification (Qual Cert Strategy) e. Pros and cons f. Schedule for Digital Design Development 12. Review design concepts with the FST 13. Present design concepts to TA for setting the final strategy a. If Yes => Set the strategy for designing individual features in Phase 3 b. If Any No => Reject continuing the design efforts
Phase 3 **Detail Design**	14. Feature Specific Design a. Modeling the primary or driving geometry for feature final acceptance b. Fleet Support Team buyoff on Discrete Feature
Phase 4 **Integration and Recomposition**	15. Incorporating Discrete feature to final part a. Early Stage i. Combine with other ii. Make Self Supporting iii. Initial Design for machined features where practical b. Late Stage i. Refine Self Supporting Design ii. Plan for Material removal for final part global requirements iii. Evaluate if prior Task 14 requires Integration or re-design 16. Signoff on Final Integrated Part a. Considerations of deviations from original
Phase 5 **Refinement and Prototyping**	17. Support Refinement a. Support of final part to build plate b. Model and check for powder removal features c. Iteration on Finish and Secondary machining feature requirements d. Simulate and iterate for distortion of predicted build failure 18. Prototype part 19. Prototype and develop secondary machining processes a. Iterate where applicable task 14-19 for applicable secondary processes 20. Testing to evaluate acceptance of final design and production method 21. Signoff review by Technical Authority

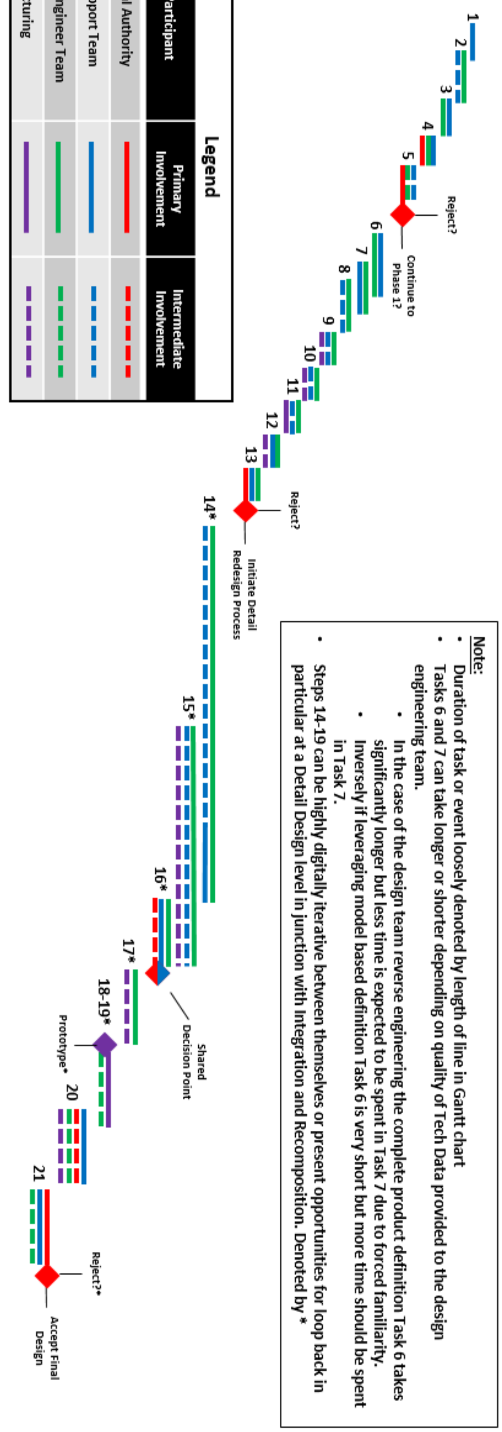


Figure **4-31**: The schematic illustrates the design process, broken into discrete phases. The participation of various stakeholders is illustrated through color and line type. The length of the line indicates the approximate relative distribution of time/effort expended during each task. Diamonds denote a critical decision or review with the primary stakeholder for that decision.

The generation of this participant analysis was not conceived at the inception of the effort, but instead was born out of reflection of the path this effort took and feedback provided by NAVAIR. The TA noted how their participation was structured - helped them understand the rationale behind the form of the AM part without consuming too much of their bandwidth. This gave them a higher confidence level in the successful airworthiness of the part as compared to previous design efforts they were involved in.

Future design research efforts may wish to keep rigorous logs of the stakeholder participation, as doing so may allow for a more apt comparison of the effectiveness of different design work flows, and may help generate better workflow models to educate the next generation of DfAM engineers.

4.6.2. Requirements and the Cost of Complexity in Design

Complexity may be "free" for additive manufacture but the cost of design is anything but free. The knowledge work of reverse engineering, participating in meetings, making decisions, and generating product definition with CAD takes an appreciable amount of time which resolves into the cost of design. The requirements associated with this effort had a discernable impact of the cost of design.

The lack of product definition necessitated over 200+ hours of labor being spent to extract design requirements. Having access to drawings or model based definition could have drastically reduced the cost associated with **Feasibility and Planning** side of the design process. The lack of design information or documented rationale behind features elevated the amount of caution warranted while redesigning this part. This caution resulted in significant time (several days) being spent to redesign individual features in a form inspired by the original. The lack of known margin built into these requirements forced significant time and effort to be expended to satisfy them. Having access to the design data would help in substantiating deviations from the requirements. NAVAIR rationalized the requirement for matching the center of mass and final mass would be easily achievable with AM because it can produce complex geometry without tooling. While this is not inherently wrong, it neglects the knowledge work required to generate the product definition which satisfies that requirement. Between 200 - 300 hours was expended to generate the product definition to satisfy these requirements to within 1 mm and 1 gram of the target.

Rapid identification and elimination of unnecessary requirements will significantly reduce developmental costs. Constraints based on the *form* of the original design - such as arbitrary geometry, center of mass, and final mass - requires labor above and beyond what is typically required to design a part that replaces the *function* of the original part. NAVAIR's dream of being able to quickly produce any arbitrary form for drop-in replacement parts will often be in conflict with limitations of the PBF-LB/M process. When those conflict exists, in is necessary to expend knowledge work to overcome them. Recognition of this price will aid NAVAIR in making informed decisions about which design efforts to undertake in the future.

4.6.3. Modeling and Design Practices

The modeling and design practices developed over the course of this case study were shown to be effective in documenting and discussing design options with stakeholders. Color coding and working with multi-bodies as outlined in Table **4-1** and Figure **4-15** from **Chapter 4 section 4.4**, reduced the cognitive workload on the design engineer by highlighting the geometry being actively worked on. When interfacing with the various stakeholder on concepts or issues about the design, these techniques leave little ambiguity in the discussion. When comparing various uncommitted concepts side by side, the color causes the feature being considered to stand out, and less effort is expended trying to understand the design space.

The complexity of the PBAR and its requirements were made more manageable by use of the DfAM+ framework. The systematic decomposition of the problem and its requirements into manageable pieces aided in quickly converging on a viable design. This reduced the risk of wasting valuable detail design labor into producing inoperable design concepts. It was helpful for building a traceable rationale behind design decisions, which aids in rational decision making. Rationalizing through the MPP at the conceptual design phase is an excellent means of incorporating considerations for primary and secondary machining when designing the As-Built state of the part, as opposed to incorporating those considerations as an afterthought or having to redesign the part on account of issues identified late in the process.

This systems engineering based design process lends itself to projects with large number of competing requirements or high value efforts where the cost of failure is an aggravating factor. Applications of AM justified predominately through a geometric complexity argument for part consolidation would benefit the most from using the DfAM+ framework to guide their design efforts. Applications with more direct requirements such as simple brackets may not warrant strict adherence to the letter of the DfAM+ framework, especially the formalized functional decomposition phase.

4.6.4. The Need for DfAM+ Design Guides

Many of the DfAM guides published by PBF-LB/M systems OEMs focus on either hard limits or espouse conventional wisdom pertaining to the AM process [29]. Discussion of using post-processing techniques applicable to PBF-LB/M are often limited to items such as defining the shape to print holes prior to manual drilling, or considering whether to recommend machining the downskin. Trade studies are useful tools for succinctly communicating the nuanced trade space of various MPP and requirements for a desired feature. Case studies are useful in illustrating some concepts of DfAM+, but not all decisions or features presented in a case study may be applicable to other components, and therefore may not warrant being incorporated formally into a design guide.

Reflection on this have led to the definition of five factors to consider in selecting what from a body of research or case study might warrant inclusion in a DfAM+ Guide.

1. The lesson must be directly abstract-able to features on other parts
2. The lesson must be generalized, i.e. cite the trend not the number
3. The lesson explores a graduated level of responses coinciding with driving requirements
4. The lesson explores the effects of coupled DfAM decision with secondary processes
5. The lesson notes when a permutation of a DfAM+ decision is likely to only be practical under economies of scale or specific other specific conditions

A guide produced through adherence to these tenants is expected to be applicable to both new and experienced AM practitioners. It can be formative in building a more pragmatic work force that recognizes the scope of design efforts required to generate a MPP that considers both additive and subtractive processes required to realize a final component.

The trade study from this design effort that most warrants inclusion in a DfAM+ guide is the options explored for producing complex internal passages. Further permutations of ways to leverage AFM may need to be incorporated to include its use for deburring or removing lightly sintered powder. Examples for methods to incorporate AFM tooling into the design of a part could be included, along with high level MPP considerations to be wary of when considering AFM for complex internal passages.

The Actuator Cavity from this design effort would be an example of a feature which does not explicitly belong in a DfAM+ guide in its current form. It immediately fails the rule 1 test because the lessons from the design of that feature are less directly applicable to a class of features on other parts. Instead showcasing down skin texture or risk associated with generating enclosed downskin geometry may be a better lessons to highlight.

Though PBF-LB/M is an impressive near-net-shape process, machining will be required for most applications. Engineers learning about DfAM without a background in primary and secondary machining will likely not have an appreciation for the nuances of work holding or locating the part in a machining center. Much of the classical design thinking underpinning the GD&T, product definition, and design of castings and forgings for subtractive processes is difficult to teach but may be directly applicable to the AM workforce. Condensing some high level overview of primary machining consideration applicable to AM would be a rather useful inclusion. Even something as simple as a check-list of generic machinist's concerns, or advice for how best to communicate effectively with machinists about machining an AM part would be extremely beneficial, as it takes significant time to learn these lessons on the job. Further concepts related to primary machining that may warrant inclusion in the DfAM+ guides for PBF-LB/M include:

- Nuances of subtractive machining mating faces of topologically optimized parts
- Indexing a machining operation locally verses indicating off of a fixture or datum
- Exploring the trade space of mesh, breakaway, and solid supports
- Understanding how surface texture and distortion in AM may affect tolerances of primary machined geometry

Any design guide would need to be a living document. Processes and design tools and constantly improving. For instance, topological optimization used to involve significant effort to generate an organic geometry inspired by the rough mesh it outputted. Today, the software workflow often include generative modeling tools that significantly reduces the time it takes to create these organic structures. Improvements such as these change the landscape for what problems this tool may solve. At the pace that AM technologies and our understanding the capabilities improve what is impractical today, may become trivial tomorrow. The DfAM+ guide must be constantly updated to reflect these trends.

Chapter 5

Conclusions and Closing Remarks

5.1. Conclusions

PBF-LB/M is proving capable to serve as a valuable near net shape fabrication process, but to satisfy many of the form and finish requirements it must be leveraged with primary and secondary machining operations. Existing DfAM frameworks strategies to incorporate considerations for other manufacturing processes were found to be wanting. Existing frameworks risked expensive design iterations or considered the requirements of these other manufacturing process late in the design, long after the majority of the part was defined.

In this work, the concept of conventional DfAM was expanded to include considerations for additional manufacturing processes, thereby creating the concept of DfAM+. With DfAM+, the DfAM decisions are integrated with considerations for primary and secondary machining processes, and other information that would serve to complete the full manufacturing process plan (MPP). A framework was drafted to be mindful of the cost of design labor, in keeping with lessons pulled from systems engineering frameworks. The framework calls for an open and auditable discourse of the rationale behind the decision to use AM along with the requirements for design. Rationalizing the impact of requirements of the features on a part to the complete MPP in the conceptual stage aids in identifying problem areas *before* significant effort is expended. Small concessions to additively manufactured geometry that can simplify the downstream MPP are identified prior to significant investment of labor spent modeling the part. By following the DfAM+ framework, the act of generating the necessary product definition will be more straightforward with fewer surprises. Though it must be recognized that the design work is never truly complete until the component has been successfully prototyped and the design is successfully tested against the requirements that shaped it. The DfAM+ framework is demonstrated through a case study.

The PBAR represents a worst case scenario of requirements and constraints that can be applied to the design of an additively manufactured part. This body of work demonstrates how one would go about designing a drop-in, functionally-equivalent replacement part leveraging the capabilities of PBF-LB/M in concert with primary and secondary machining – while being mindful of the scope of effort required to do it right. It will be up to the practitioners to take the lessons from this work — knowing that it is possible to design parts for AM to satisfy similar arduous requirements, but always asking the question whether or not doing so is worth the full price in developing the complete MMP.

To better train the next generation, a living document of DfAM+ design guides should be commissioned to impart key takeaways of the nuances of leveraging AM with other manufacturing processes. Tenants for generating such a document are outlined, so the nuances of DfAM+ can be communicated along with a place to start.

After exposure to these concepts, a DfAM engineer will be trained to consider generating a slightly less weight optimal design for a one-off bracket IF that concession would drastically reduce the cost of tooling for primary machining. This engineer will pragmatically weigh the cost of complexity against the expected performance gain. Or, at the very least, will reach out to other manufacturing disciplines to leverage these other processes with AM and to better understand the role AM should play in the modern industrial world.

Considering the holistic impact of DfAM+ decisions on cost and performance will move engineers, industry, and academics beyond asking what they “can” do with AM, and equipping them to decide if AM is the “right” solution.

Failure is just as important as success, and we—as academics—should be open to sharing any pitfalls or failed attempts as those lessons are often the most important.

5.2. Closing Remarks

The aviation sustainment community is constantly reminded of the consequences of design engineers pitching designs over some philosophical wall that separates design and manufacturing. The author has spent the better part of three years, prior to graduate school, addressing the issues that arise from this practice. The study of design for manufacturing was born out of the recognition of these issues, as engineers began to live with the consequences of those mistakes. It is frightening how many academics hold up examples of "good" DfAM that glosses over the challenges of qualification, or primary and secondary machining. Many of these examples, such as the GE bracket challenge, are by the definition of DfAM+ incomplete. If we want to accelerate AM's integration into industry, a good starting point is by showing the full story of the design process. Even if it means showing the failures arrived at along the way.

The days of submitting a shape of the final state of the PBF-LB/M part and considering that work sufficient to demonstrate this technology in academic papers should come to an end. Proper design work in this space should include consideration of product definition to adequately describe the plan to take an As-Build part to a finished machined state – or they scope their claims to the limits of the work performed. Forethought towards verification and validation should be essential, as without these key steps, the AM components may do nothing more than serve as expensive paper weights. Additive Manufacturing is far more capable than that, and it's time we show it.

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