3D Printing Technology Insertion: Sociotechnical Barriers to Adoption

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Abstract

Since the initial development of three dimensional printing (3DP) in the 1980s, companies have relentlessly researched for applications of the technology. The potential benefit is large, beginning with improved cost and schedule to manufacture plastic and metal articles. As such, governments and industry from advanced economies continue to invest heavily to accelerate 3DP adoption. Amid advancements in the pillars of three dimensional printing – the technology, material, and software – practitioners across industries are steadily deploying 3DP in product development, prototyping, and small scale production of parts and products. However, a large gap remains between promise and the reality of larger scale adoption. The potential benefits, risks, and specific steps to adopt and realize the benefits are not clearly understood, resulting in overly zealous (at risk) or overly cautious (opportunity avoided) approaches to 3DP adoption. Traditional manufacturers rely on decades of know-how in manufacturing practices across a large portfolio of parts, making first steps on a path to adopt new processes more challenging.

This paper identifies the variables that complicate or impair judgement when considering the adoption of 3DP. A systematic approach to evaluate 3DP adoption across a portfolio is needed. A methodology is proposed to analyze the relative value of 3DP at the part and product system level for prototyping and production. The outcome is a framework that combines part-level feasibility with systemic benefit of cost and schedule improvements as prototyping and production alternatives. In building this framework and in interviews with experienced manufacturers, several key insights were gained. Part by part consideration of 3DP feasibility is daunting, while adoption requires readiness not only of 3DP technology but also the receiving systems and organization. By viewing 3DP insertion as a sociotechnical system implementing the changes, attention is drawn to the tacit knowledge of critical characteristics in existing manufacturing processes, design for manufacturing decisions embedded in existing part assemblies, the pre-processing and post-processing capabilities available to shift 3DP feasibilities, and the alignment of organizational learning across parts.

Keywords— additive manufacturing, 3D printing, technology insertion, sociotechnical systems

1. **Introduction**

For decades the additive manufacturing industry has made significant investment and progress in advancing three dimensional printing (3DP) technologies. Starting from stereolithography in 1986, today there are numerous competing technologies for fabrication ranging from thermoplastics to metal. Their common characteristic is extraction of shape information from three dimensional product models and manufacture by layering the materials in cross sections to produce a final shape. One of the most distinguishing features of 3DP is the ability to create "high geometric freedom" shapes, thus holding "the potential to revolutionize product design". [1]

The applications, from defense to consumer electronics to biomedical, of additive manufacturing have increased significantly in recent years. However additive manufacturing today accounts for less than one percent of all manufactured products in the United States.[2]

1.1. Categories and definitions of 3D printing technologies

There are many categories of additive manufacturing technologies. The ASTM F42 Committee defines additive manufacturing as "a process of joining materials to make objects from 3D model data". [3] According to the ASTM, the seven primary categories of additive manufacturing processes include binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization.

1.2. Recent industry examples

The aerospace industry has been an advocate of 3D printing technology and demonstrated significant interests in advancement of the 3D printing technology (including material) and its applications. In recent years, the combination of technology maturity and experience building have resulted in the proven commercial applications of 3D printing for prototype and production intent usage in the industry.

GKN TiPOW Research. GKN Aerospace commences a 3-year collaborative research program to develop titanium powder optimized for AM of aerospace components. The TiPOW (Titanium Powder for net-shape component manufacture) program is backed by UK's Aerospace Technology Institute and Innovate UK. The program's objectives are to minimize cost while satisfying the rigorous standards and explore the reuse and recycling of titanium material. GKN Aerospace will supply the turbo exhaust case and compressor intermediate case for Pratt & Whitney.[4]

GE T25 Sensor. AA approves the first AM part, GE T25 Sensor, to fly inside GE's commercial jet engine. The GE T25 sensor houses the compressor inlet temperature sensor in the GE90-94B engines (used on Boeing 777). The part will be produced with cobalt-chrome alloy. GE is currently testing AM-produced fuel nozzles for the next generation LEAP engine and developing AM-produced fuel nozzles for the GE9X (the largest jet engine ever built). [5]

Airbus A350XWB. Airbus and Stratasys joined efforts in 2013 to develop and certify 3D printing for use in A350 XWB. Over 1,000 flight parts for the A350 XWB were produced using ULTEM™ 9085 resin using FDM technology. The ULTEM™ 9085 resin is certified to an Airbus

material spec and is flame, smoke, and toxicity (FST) compliant for interior aircraft applications. [6]

MTU Aero Boroscope Bosses. MTU Aero mass-produces nickel alloy borescope bosses for the PW1100G-JM geared turbofan (GTF) engine. The borescope bosses are part of the turbine housing for the A320 neo's GTF engine and allows access to the inspection of the blades using a borescope. MTU plans on building 16 parts per build, up to 2,000 parts/year. MTU and EOS are collaborating to optimize the surface finish of the component. [7]

Rolls Royce Trent XWB. Rolls Royce uses additive manufacturing to produce the largest 3D printed civil aero engine part – Trent XWB bearing. The bearing is made from titanium and has a diameter of 1.5 meters. It is comprised of "48 airfoil-shaped vane components" each individually produced using EBM technology. Rolls Royce has used AM for 5 years to repair components but is now using AM to make large components from scratch. The bearing will be used in flight for the first time in 2015. [8], [9]

1.3. Related Work

Studies to date have been primarily focused on technology readiness or cost effectiveness as the barriers to technology adoption. [2], [10], [11] Other researches have focused on the studying the dynamics of technology adoption in the context of network externalities and assessment of viability. [12], [13] Our research acknowledges those factors and introduces a sociotechnical component that is endogenous to the technology adoption cycle.

Farzin describes an approach to calculating the optimal timing to adopt a technology. Leveraging dynamic programming framework, a firm can model the ideal timing to employ a technology especially when the decision is irreversible and uncertainties exists with the maturity and benefit of the technology adoption.[14] Disparities in technology adoption across countries have also been studied. An explanation of this disparity is dependent on the level of "world knowledge" and a country's inherent barriers to technology adoption.[15], [16]

The cost drivers and cost models of 3D printing has been widely researched and published. Lindemann compared the four main cost drivers of additive manufacturing: build rate, machine utilization, material cost, and machine investment cost.[17] Hopkinson outlined the cost breakouts of a producing a part using different 3D printing processes and presented a cost model based on the calculated average cost per part.[18] Ruffo et al. introduced an activity based approach to cost modeling, with consideration to indirect costs, for selective laser sintering.[19]

The interplay during product development between foreground product designs and background design intent have been well documented. Nonaka characterizes the knowledge management cycle during product development as activity that forms both tacit and explicit knowledge of the product system.[20] Kimura applied this view of deep product development knowledge to CAD systems and the development of production molds.[21], [22] James assessed measure of product complexity in considering the technology insertion into a new variant (geared) of an aerospace turbofan.[23]

2. **Problem Statement**

2.1. Product Development as a Sociotechnical System

Studies on three dimensional printing feasibility have been focused primarily on the technology readiness, part value (cost and time), and process planning (timing, externalities, etc.). Our research focus is on the endogenous sociotechnical dynamics that affect the technology adoption cycle, from which we investigate the attributes that affect the part design, prototype, tooling, and production of parts. Our objective is to expose the technology adoption risks and benefits at a both local (part) and systematic (product organization) scale as they influence product development choices.

Based on several interviews with manufacturing process experts [24], [25], the authors focus was drawn to the barriers to adoption beyond value analysis. The industry experts emphasized that the resultant cost, quality, and schedule of a manufactured part in many cases is the result not simply of an automated process, but instead a combination of technology, process, and the tacit knowledge which aligns the materials, the designs, and the manufacturing environment. An existing part as-designed and as-manufactured embeds a legacy of previous choices in the part itself, and also the pre-processing, material choices, the manufacturing environment, the role of quality during production, post processing, and verification and validation. This history of choices as background knowledge is both tacit and explicit. Even if a traditional manufacturing technology (e.g. machining) is replaced by 3DP, the remainder of elements in the total engineering and manufacturing process may be still aligned with the previous process. Early failures due to such misalignment may in turn lead to an adoption averse organization.

This consideration of the total technical and social systems for product development treats the product part – and its actual cost, scope, quality, and timeliness – as an emergent characteristic of engineering as a sociotechnical system. [26] In this way insertion or displacement of just the part, or a process component, may lead to unanticipated consequences, frustrations, and risks. Likewise, by considering the broader design of the product development system when inserting 3DP, these frustrations and risks may be avoided.

The problem facing a manufacturer considering displacement of existing processes with 3DP may be daunting if the analysis requires a part by part comparison of the multitude of evolving 3DP tools and materials to existing processes. As shown in Figure 1, the need is for a systematic method to filter and prioritize parts in the context of product and business value, to capture and evolve knowledge about 3DP through this process, and to accelerate learning across the organization by allowing association of insights across the portfolio of parts.
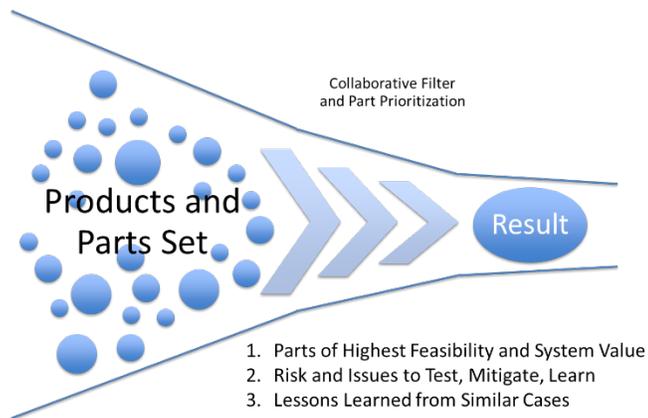
Figure 1: Challenge to Filter, Prioritize, & Learn Systemically

3. <u>**Approach**</u>

For many companies their current production techniques are backed by years of know-how leading to high quality, reliable parts/ systems. Know-how for new engineering and production methods takes time to develop. In this paper we ask:

- How to adopt new 3DP product development and production methods at an optimized pace while minimizing risk of poor quality and loss of know-how?

Recognizing this key question, the approach should support existing product and process experts in the field so they can:

- More rapidly evaluate and prioritize potential application of additive manufacturing to a specific product system

- More rapidly capture lesson learned and insights from this evaluative process, linked (tagged) to product characteristics, process, and additive manufacturing options

- More efficiently share adoption rules and insights across product systems and business units

4. <u>**Proposed Method**</u>

4.1. Overview of the Method

The framework for accelerated adoption of 3DP begins with mapping of major knowledge areas needed to evaluate candidate parts. Figure 2 shows product knowledge (P), 3DP tools and material knowledge (T), tacit knowledge of product system engineering, production, and quality (K), and how these combine across an assembly as compared to an alternative baseline manufacturing process. Beginning on the left of Figure 2, an existing product system is represented in a bill of materials (BOM), often containing tens of thousands of parts. The challenge is to search amongst these part candidates and prioritize those that are both feasible for 3DP and valuable to the firm when considering cost, schedule, and product quality at the volumes (and margins) for the business.
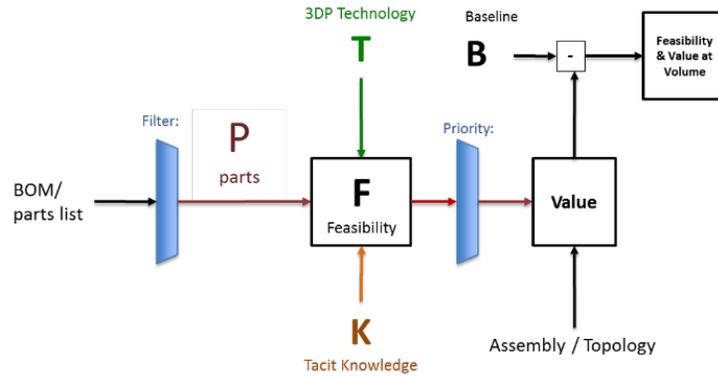
Figure 2: Product, Technology, and Knowledge Combine to Filter & Prioritize

Moving from left to right, from a BOM/parts list to Value, requires attention from various teams across the organization, especially when considering tacit knowledge of part unique production requirements. In many case those teams with deep subject matter knowledge of partwise engineering and production at quality are not the same teams with deep knowledge of market facing volumes, margins, and customer utilities.

4.2. Definition of Terms

Below is a list of terms and corresponding definitions that are used in our methodology.

The first set of variables refer to the product system being prototyped and produced.	
p	Part (BOM)
p_n	the nth part
p_B	baseline part as generated by existing manufacturing process
p^e	engineering prototype part
p^m	(mfg.) production intent part
S	Product system
The next three variables refer to the options for manufacturing the part.	
T	Additive manufacturing technology; tools and material
B	Baseline – the existing (legacy) manufacturing process
K	Background knowledge; know-how
The terms below are for evaluating the production options	
$F()$	Feasibility
$V()$	Value
d	Duration
c	Cost
q	Quality

4.3. Outline of Methodology

The framework begins with the filtering of the Bill of Materials/parts list (BOM) for parts both insourced and outsourced. Outsourced parts will not be considered and insourced parts will further undergo a part intent filter to classify the parts into prototype intent and manufacture intent.

The respective part attributes for prototype and manufacture intents are mapped against the 3DP Technology (T), both tools and materials, for feasibility analysis. Attributes that affect prototyping and production of parts can include the complexity of the part geometry and topology, dimensions, tolerances (dimensional and physical properties), material type and diversity, intended use and environment, appearance (surface finish and aesthetics), strength, certifications, and other relevant elements. In prototyping, concept validation is often the focus and rapid prototyping techniques typically help reduce the product development cycle (time and cost). However, this does not necessarily translate to manufacturability or large scale manufacture as the tools used in prototyping are sometimes not employed in production. This anomaly often leads to well-known risks: namely manufacturability and feasibility. The manufacturability addresses whether a part can be produced to production intent specifications and the feasibility considers the time and cost, which includes sustainability and the yield rate.

As shown in Figure 3 below, the analysis compares the dimensional/geometric, accuracy/tolerance, material, mechanical properties, and quality dimensions of the part and the selected 3DP Technology to learn what attributes are within and outside of the limits for the part (p) and 3DP Technology (T). The feasibility analysis, F(p,T), relies upon part, tool, and material attributes as shown in Figure 3 below.

Some combination of attributes, for example the part dimension and machine capabilities, may quickly filter out the part for consideration. However, some combinations may be nearly feasible yet may be compensated by background knowledge (K), discussed in more detail in the next section. Rather than simply a yes/ no filtration, the analysis exposes the basis of feasibility including risks, with an emphasis on uncertainties to decrease and/or readiness to increase across the p, T, K set.
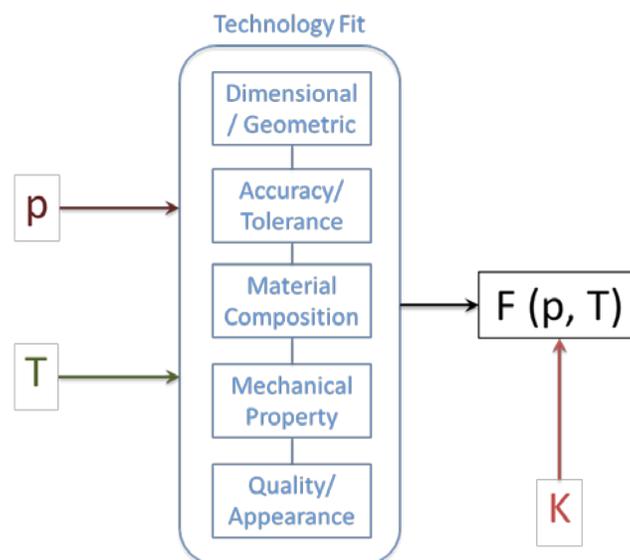
Figure 3: Part, Tool, Material Combination Feasibility

4.4. Visualization by Feasibility and Value

In an example shown below in Figure 4, a prototype intent part (p_1^e) may be deemed slightly less feasible but has more systemic value than the baseline part. That same part for product intent (p_1^m) may have more uncertainties in feasibility and systemic value compared to both the prototype intent and baseline parts. The baseline part may be highly feasible but with somewhat limited systemic value. The visualization helps to prioritize and differentiate the parts for optimal 3DP insertion decision making.
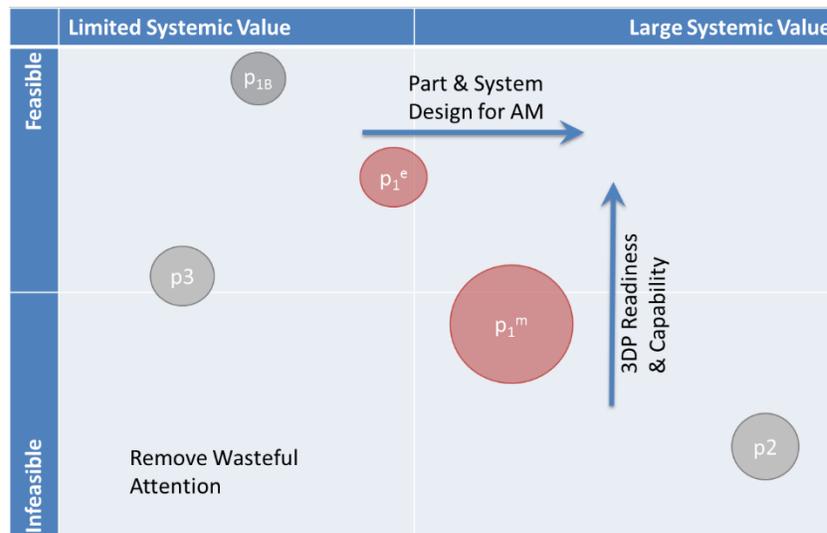

Figure 4: Comparison of Feasilibty & Systemic Value of 3DP compared to Baseline

An aspect emphasized in the feasibility analysis F(p,T), is the consideration of the background knowledge (K, see Figure 5 below.) The background knowledge (K) may indicate what parts are feasible under current 3DP Technology (T) and tacit know-how such as post-processing capability. The inclusion of background knowledge (K) also encourages the exploration of the systemic value of the assessed part compare to those of the baseline.
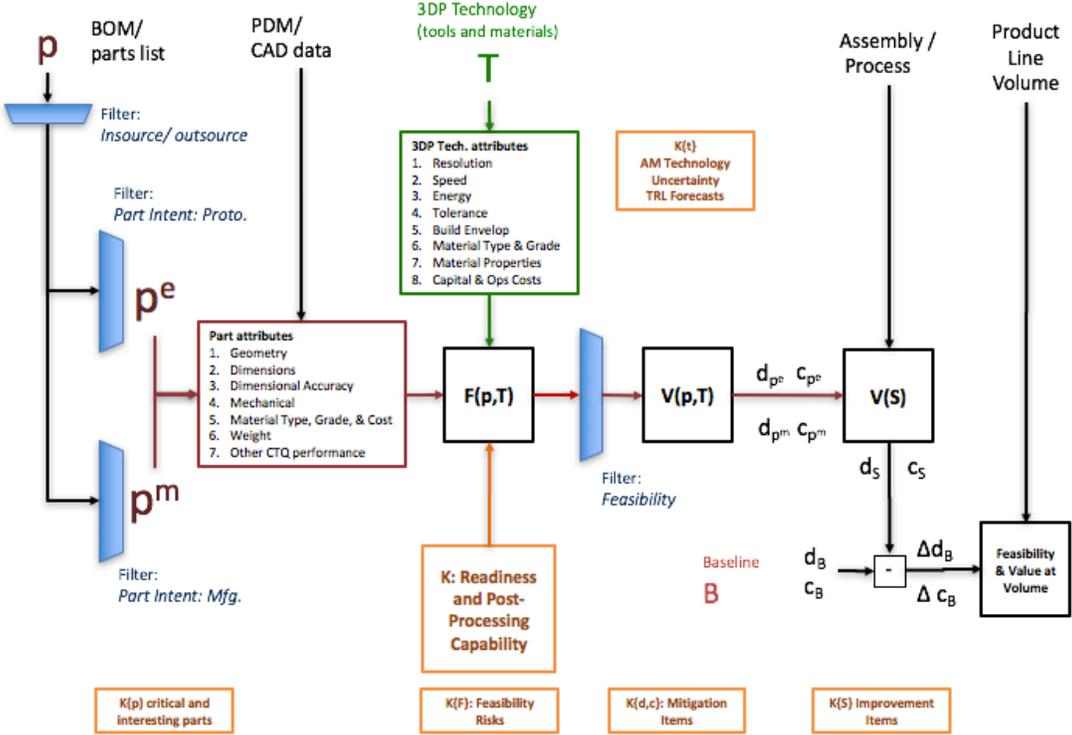
Figure 5:Framework with Parts, 3DP Tools and Materials, and Process Knowledge

Taken together, a more detailed view of the method is shown in Figure 5 above. As the large set of total BOM parts is filtered and prioritized, the steps include the ability of experts to review, comment, and in some cases adjust the analysis. At first, with few parts and product systems reviewed, the method will be helpful but still limited to the source knowledge on 3DP technology provided. However, as more and more parts across a portfolio of product systems and 3DP tools and materials are analyzed, then similar parts, technology, and issues (p,T,K) will be linked across the organization. In particular, as new 3DP tools and materials emerge, this structured knowledge approach can allow an accelerating consideration of adoption across most closely related parts in the organization.

5. **Example of Framework Usage**

5.1. Bill of Material for an Engine Part Assembly

This example starts with a high level bill of material for a turbine engine part assembly. A turbine engine can have over 60,000 unique parts in its Bill of Materials (BOM); in this example we will explore a subset of those parts, focusing on the compressor and combustion sections of the engine.

Key parts that make up those sections include the compressor vane ring assembly, compressor blade assembly, combustor blade assembly, shaft, bearings, seal rings and sleeves, expander springs, spline spacers and rings, bearings, couplings, and inlet temperature sensors.
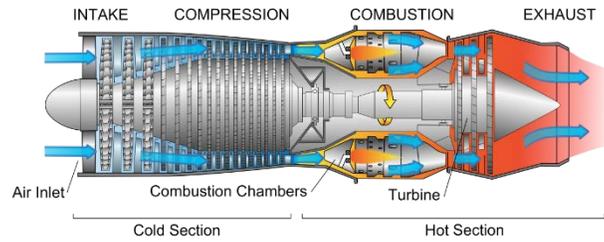
Figure 6: Typical Jet Engine Diagram[27]

The initial step is to filter the compressor and combustion subassembly parts for insource and outsource manufacture. Only insourced parts will undergo the feasibility analysis F(p,T) as the know-hows for outsourced parts are typically exogenous in this framework. Of the key compressor and combustion section parts we assume the bearings, seal rings and sleeves, expander springs, spline spacers and rings, bearings, and couplings are outsourced, while the compressor vane ring assembly, compressor blade assembly, combustor blade assembly, and fuel nozzle are insourced.

5.2. Part Usage Intent: Prototype vs. Production

Parts during the design and product development cycle are often instantiated more than once. The next step involves filtering the insource parts into prototype intent (p^e) and production intent (p^m). Each part will be evaluated based on its part attributes for the usage intent. For example, early stage prototype intent parts, such as a look-alike prototype, may prioritize on dimensional or "fit" validation and therefore often have different part attributes compared to those of a production intent part. In this scenario, the feasibility analysis should be designed to meet the prototyping requirements and not the exhaustive requirements of those for the final article. However, if the objective was a feasibility analysis for a production intent part, then it will likely be subject to the same requirements, assuming the proper test protocols are known for that 3D technology and material.

5.3. Feasibility Analysis for 3D Printing

Once the parts are filtered by usage intent (p^e or p^m), their respective part attributes are compared to the 3DP Tech attributes. The 3DP Tech attributes are a summary of the 3DP Technology (T), which includes the available tools and materials for 3D printing. printing tools and materials, denoted as T and part attributes. The 3DP Technology (T) example is the Arcam Q20 industrial metal 3D printer, which employs Electron Beam Melting (EBM) process and is compatible with titanium and cobalt materials. The specific known compatible materials are the Arcam ASTM F75 CoCr (Cobalt-Chromium) Alloy and the Arcam Ti6Al4V (Titanium) Alloy. The build envelope for the Arcam Q20 machine is 350mm x 350mm x 380mm in the x, y, and z dimensions.

For part attributes, either p^e or p^m, it will be existing part specifications with no redesign. To start, in the compressor vane assembly, it consists of the compressor ring of over 1200mm in diameter and compressor vane stator blades with common dimensions of 155mm x 40 mm x 40 mm and usually made from titanium. The compressor blade assembly contains the compressor blades of similar size to the vane stator blades and the compressor disc of over 600mm in diameter and both made from titanium. The combustor blade assembly contains the combustor disc that is

over 600mm in diameter and the blades are also similar in size to the vane stator blades, and with cooling holes for film cooling. The combustor assembly is commonly made from nickel superalloy and sometimes the blades are made from ceramic to withstand the extreme operating conditions. The fuel nozzle is commonly produced from cobalt alloy.

Knowing the 3DP Tech. attributes (T) and part attributes (p^e, p^m), the next step would be feasibility analysis of technology and part or the F(p,T) in the framework. The compressor vane ring, compressor disc, and combustion disc parts are too large to be 3D printed in one piece by the Arcam Q20 printer. Furthermore, the combustor disc is made from a material that is incompatible with the printer. For the blade parts, the compressor blade dimensions are within the print envelope constraints and the material is available and compatible with the Arcam Q20 printer. However, while the combustor blade dimensions are within the print envelope constraints, the specified material is incompatible with the printer. For the fuel nozzle, it is also within dimensional constraints and made with a material that is available and known to be compatible with the printer.

Assembly	Sub Assembly	Dimensions	Material	Feasibility (p, T)
Compressor	Compressor Vane Ring	1200mm diameter	Titanium	Low confidence, due to dimensional constraint
Compressor	Compressor Disc	600mm diameter	Titanium	Low confidence, due to dimensional constraint
Compressor	Compressor Blade	155mm x 40 mm x 40 mm	Titanium	High confidence
Combustor	Combustor Disc	600mm diameter	Nickel Super Alloy	Low confidence, due to dimensional & material constraints
Combustor	Combustor Blade	155mm x 40 mm x 40 mm	Nickel Super Alloy or Ceramic	Low confidence, due to material constraint
Combustor	Fuel Nozzle	Comparable size to combustor blade	Cobalt-Chromium Alloy	High confidence

Figure 7: Feasbility Analysis of Aircraft Parts for 3D Printing

The post processing capability, denoted K in the framework, is an important criterion in the F(p,T). Post processing involves heat treatment to yield the strength and machining to achieve surface finish and tolerance requirements of the printed part. Without the required post processing capability, the printed part will invariably not meet specifications even with technology ready 3D printers and materials. For example, in the case of the compressor vane blade, the feasibility of 3D printing may be greatly affected if the design of the blade contains holes for film cooling. Since the blade usually requires high surface finish, post processing the surface is almost always necessary. This requires sufficient machining capability, such as in-depth knowledge of electrochemical machining, so as not to block the holes or corrode the part though the process, rendering the part unusable. This is one of many examples of why post processing capability is germane in the feasibility analysis for 3D printing. Finally, parts that satisfies the F(p,T) requirements will pass the feasibility filter and undergo part value analysis.

Value Analysis of 3D Printed Part

The parts will be evaluated for part level value, $V(p,T)$, based on the duration and cost to manufacture for prototype intent (d_p^e, c_p^e) and production intent (d_p^m, c_p^m). These metrics are compared with current known duration and cost figures using existing manufacturing practices. A part that demonstrates superior duration and cost with 3D printing would be a good candidate for technology insertion. Conversely a part that lacks duration or cost advantages when 3D printed should not be eliminated automatically. For a prototype intent part, the duration (d_p^e) often carries more weight than the cost (c_p^e). The part level value, $V(p,T)$, for a production intent part may be more complex as duration (d_p^m) and cost (c_p^m) may hold similar importance. However, even in the scenario that a part is costlier to make, it may still deliver systemic benefits that are often overlooked in the local part level value analysis.

The systematic value analysis, $V(S)$, aims to uncover the systemic benefits of duration (d_s) and cost (c_s) for the assembled component. This analysis accounts the total time and cost to produce the assembled component with the 3D printed part and benchmarks those metrics against those of the current produced component. A component that reveals a duration (d_s) or cost (c_s) saving may generate a discussion if benefits warrants a part to be 3D printed.

An example of systematic value would be the fuel nozzle where its complex geometry has traditionally required multiple investment casted parts that are later welded to join the parts. The final part is both cost and labor intensive. When 3D printed, the part can be produced in a single run and without the need of welding, delivering a stronger part while requiring less labor. Identifying similar sub-assembly parts would potentially uncover tremendous cost and duration savings for the stakeholders.

6. Expected Value of Framework Implementation

6.1. Complement to Value Analysis

Several techniques have been in regular use to account for and calculate the potential value (e.g. material cost reduction and supply chain robustness) upon insertion of 3D printing. These techniques can be used to analyze potential benefit, yet in some cases do not address why hidden assumptions or ill-structured costs might hinder organizations from adopting the new processes.[28]–[30] As a complement, this paper's framework emphasizes the linked consideration of background knowledge of processes along with the foreground knowledge in product design and engineering. As discussed earlier (Suzuki et. al.), background knowledge is the tacit knowledge embedded in an organization's experience while foreground knowledge is the explicit knowledge shown in part design and production, such as engineering drawings and specifications.

This framework complements value analysis by proposing a proactive approach to stimulate and address these background knowledge areas as part of exploration of value analysis for a portfolio of parts. Many past assumptions and experiences with traditional manufacturing may inform and differ from the direct value analysis; these concerns in the organization need to be addressed to allow initial steps and early pilots of the new process.

Readiness Assessment

The framework also generates insights regarding the technology readiness and firm readiness to adopt 3D printing for the prototype and manufacture of a part. The feasibility analysis of the part (P) in combination with the 3DP Technology (T) shows technology readiness of producing a particular part. This feasibility analysis considers the likelihood of satisfying the part attributes with a specific 3D printing process and material availability and can be viewed as an another example of foreground knowledge. However good technology readiness does not necessarily translate to high feasibility of producing a part. The tacit knowledge that is embedded in manufacturing routinely dictates the cost and quality of the finished article. An example of this tacit knowledge is the ability to identity materials and apply proper heat treatment to result the required yield strength. This tacit knowledge is often a core know-how and competitive advantage for a firm and thus considered the firm readiness. The framework considers this readiness (K) in the feasibility analysis, allowing the stakeholders differentiate and focus on the different readiness factors.

6.3. Reverse Analysis of Value to Parts

The framework can potentially produce reverse analysis of value to determine the parts. This approach begins by establishing a desired cost and duration improvements, and the framework will identify the parts that have various feasibility of accomplishing the targets. To enable reverse analysis, the feasibility analysis F(p,T) should first be completed, along with the local value analysis V(p,T) and systemic value analysis V(S). The reverse analysis introduces a top-down approach to value analysis, starting from the cost and duration targets, giving the different perspective that some stakeholders may require.

7.**Conclusion**

In building this framework and in interviews with experienced manufacturers, several key insights about this approach were gained.

The part by part consideration of 3DP feasibility requires technical know-how in the design, prototyping, pre-processing, production, post-processing and quality characteristics of the part in consideration. Experienced manufacturers possess this know-how for their baseline traditional processes, yet consideration of part by part in a BOM would simply be a stepwise, tedious, and very slow search. The required tacit knowledge is typically spread across multiple teams and locations. Therefore, accelerated adoption should not proceed part by part. Whereas early in our framing of the approach we assumed an algorithmic selection of 3DP part candidates, deeper consideration pushed us to recognize the limits of a purely automated approach.

This method's emphasis on a "human in the loop" exploration of 3DP insertion recognizes that tacit knowledge of baseline processes, embedded from years if not decades of organization experience, need be stimulated to expose relevance (or not) of the accepted wisdom of the firm to the new process. Engaging existing product and process experts in the field helps to generate explicit knowledge – in a form that can be shared, tested, and questioned across teams. This social process may be necessary for full consideration of 3DP which displaces proven processes at quality,

cost, and schedule well understood from past experience. The awareness and willingness of human teams to expose and unlearn past assumptions was seen as a significant barrier to early steps of considering 3DP.

Thus the framework stimulates a first step by filtering candidate parts and subsystems with up to date combination of the latest material and 3DP tools. Yet the authors now view the framework primary purpose to stimulate team of teams dialogue more quickly and efficiently. The active engagement of cross-functional experts in search of the trade space is meant to accelerate their situational awareness of the systemic feasibility and value, rather than partwise feasibility.

7.1. Limits and future work

This paper presented a challenge and framed a method for improved adoption of 3DP in organizations with significant legacy know-how and a large part portfolio. Organizations starting with "green field" development may be able to rapidly displace old or acquire new product development teams and know-how, thus avoiding the sociotechnical barriers that this method addresses.

In this paper an example was described as a basis for thinking through the method. While more detailed algorithms for filtering and prioritizing parts were developed by the authors, these have not yet been validated and thus are not presented in this paper. Future work may include deployment of a prototype system based on the method with observation of the adoption rates across teams. Formal linkage to existing value analysis and value engineering methods would strengthen the cost and duration calculations in the portfolio filters and prioritization.

7.2. Acknowledgment

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