Transdisciplinarity and the Future of Engineering
B.R. Moser et al. (Eds.)

doi:10.3233/ATDE220679

A Cross-Functional Approach to Metal Additive Manufacturing in Enterprise

Khaalid MCMILLAN[ab,1], Mehdi HAMID[a], John TOROK[a], Kyle OLSON[a], James UTTER[a] and Anthony TIANO[a]
[a] *International Business Machines, Corporation, USA*
[b] *Global Teamwork Lab, MIT, USA*

Abstract. Diverse internal capabilities are to be developed and connected to enable rapid and robust design and manufacturing of additively manufactured parts to meet the needs of mid to low volume production gaps in a large orgnization. This process includes elements of Design, Manufacturing, and Supply Chain followed with the application of application of modeling methods to simulate the additive manufacturing process of the part to reduce manufacturing related redesign. Akin to the traditional development process of design, analyze, prototype and evaluate, this process aims to leverage digital technologies and cross-functional expertise early in the design process to reduce time to market delays and late findings. This process aims to focus feedback from design, predictive modeling, manufacturing, and supply chain engineers during the concept generation process. The model is used to inform the concept using tacit knowledge, simulation, additive manufacturing, and functional prototypes to reduce late and costly changes to the design later in the product development process and is modeled using a Design Structure Matrix to evauluate improvements in the new process. The model has shown to reduce the feedback loops required to take a design to completion.

Keywords. Metal Additive Manufacturing, Finite Element Modeling, Digital Warehouse, Metrology, Materials Science, Part Qualification

Introduction

Additive Manufacturing (AM) has become much more prevelant in industry after initial adoption for prototyping uses. This has included both polymer and metal AM methods, but has since gained significant adoption in low volume, high precision applications with very robust quality control measures in place. AM, like various Traditional Manufacturing (TM) methods, has a wide variety of applications requiring a rigorous approach to identifying and implementing an AM sourcing strategy that includes leveraging tacit knowledge within the organization[1].

Building upon a framework to develop a structured process for adoption of AM, this paper seeks to implement and improve upon this process, as well as provide insight into the transformational elements required to integrate AM technologies into an enterprise organization’s well established design, release, and sourcing strategy.

Because AM tools are a relatively new set of technologies there is a significant level of effort assoicatied with embedding understanding, capability, and understanding quality controls within an established product development process that are different

[1] Corresponding Author, Mail: kmcmill@us.ibm.com

from the mature TM approaches in use today. As companies shift toward Industry 4.0 (I4) solutions [2, 3], new ways of working can be used to ease this transition.

This paper argues that the adoption of AM in a production environment, requires a collaborative effort between subject matter experts from design, manufacturing, and procurement teams. This cross-functional collaboration will help industries achieve transformation of engineering practices through a transparent, less disruptive, and conscious approach.

2. Traditional Design, Manufacturing, and Sourcing Process

Traditional manufacturing has evolved over. As products became more complex the roles of engineers and business leaders became more dyhamic resulting in a complex set of interactions within an organization. This effect is driven by time to market pressure, increased workloads, and detailed subsystem development critical for product delivery. Because of this, large engineering companies have developed a tightly controlled product development process that has clearly defined roles, responsibilities, and process flows.

As capabilities increase and production became diversified, supply chains subsequently became more complex and geographically dispersed and therefore forced the need to closely monitor inventory, supply chains, and lead times to drive business results.

The design of a physical product in a mature engineering product development organization will typically be evolutionary with high risk elements of the product being well known. The design engineering team will begin to evaluate block diagrams and "back of the napkin" designs that begin to define the early concept stage of the design point. Once there is a generally accepted design concept the designer may then transfer the 3D design to another engineer to perform performance modeling such as structural or thermal modeling to provide early feedback on the design point. At this stage the mechanical analyst and design team work closely over a period of time to come up with anoptimized design which deliver the highest performance for lowest production cost.

Subsequently, the parts are prototyped for high-level form, fit, and function feedback. This is where AM has currently found its most value in organizations, but generally machining and soft-tools have been used as a closer representation to the final product. Machined parts tend to be used as a proxy for the final machined part or casted parts. In the same light, soft-tool molds would be used to represent final injection molded parts. All of which have significant lead times and higher pricing at low volumes. This is an iterative process as well with feedback driven by function and fit evaluation (Figure 1).

The prototyped parts are tested as closely to application until satisfactory performance criteria is met. The process listed above is repeated until the design is finalized and accepted in simulated testing then is released to manufacturing.

The manufacturing work effort is generally started by identifying a sourcing strategy for all the parts of the product. This would encompass identifying the geographies where production has the least cost per tool and unit, their quality control capabilities, and level of service through the tool bring up process.

This process involves the manufacturing supplier running mold flow or other tool analysis software to optimize the quality, repeatability, and throughput then providing design changes to accommodate a robust manufacturing process. This analysis may drive further revisions in the design to meet manufacturability requirements based on geometry, material, and tolerancing. This would typically require some level of negotiation between the internal design team and supplier which leads to further delays in the process and requires more modeling and validation efforts. This process would repeat until the quality of the final product is acceptable.

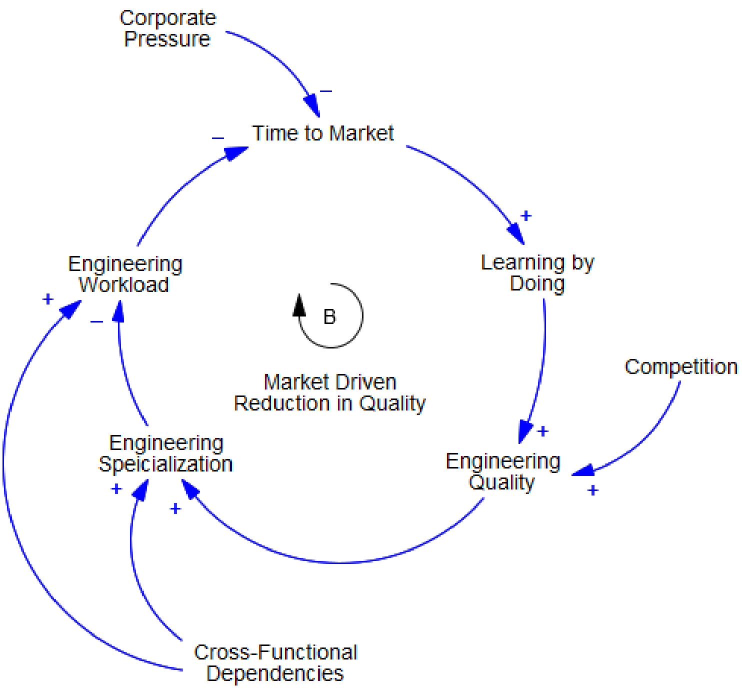

Figure 1. As corporate pressure rises, engineers are less able to spend time learning by doing, reducing the quality, which in turn reduces their ability to specialize in a subject area and increasing workload to reduce the time to market for their products.

Typically the sourcing strategy is established followed by capacity planning. In this process, planners tend to determine the timeline and volume required for orders to meet business goals. The considerations here are driven predominantly by time and cost considerations. Elements associated with time would typically need to factor in tooling set up, production run time, shipping time from the country of origin (CoO), delays through customs, last mile shipping and receiving. The factors associated with cost include storage and maintenance of the tooling, as well as any minimum order quantity (MoQ) that would established by the supplier to justify their cost to bring up the tooling and run their machines. The supplier analyzes tradeoffs by dedicating the machine time to the requested job relative to another that could yield higher profit, forcing the business leaders to negotiate win-win scenarios. Finally, the last cost consideration for the business would be the cost to hold inventory which may be significant if production volumes don't align with MoQs.

2.1. Analysis of Traditional Practices

There are many beneficial characteristics of the traditional manufacturing process flow, especially given the best practices developed by every organization through the years. Most organizations have worked out the kinks in their process and only revisits them if a crisis occurs. Traditional manufacturing process flows allows for a sequential and well understood structure from concept to delivery and permits stakeholders from each step in the process to establish their needs and requirements with dedicated attention from the design team. This process also incentivizes large order quantities and economies of scale at a single supplier allowing for lower unit cost while deepening of the relationships between the supplier and design team. The interaction time between the designers and suppliers allows for better future part design for manufacturability by better understanding of the supplier's manufacturing capabilities and limitations. Finally, the biggest benefit to the traditional approach is the pool of available designer, modeling analyst, manufacturing suppliers, and supply chain professionals that are available to support the traditonal processes set up in various organizations.

There are pitfalls to this process, mostly associated with time and cost. With this approach the design team will generally be responsible for several releases of the design prior to full production driven by several feedback loops driving possible delays in the schedule. This can be shown in the Design Structure Matrix above as elements in the lower left triangle of the matrix indicating feedback loops. This results in multiple redesigns of the product driven by internal and external influences that all require time to analyze and reanalyze the same part throughout the design cycle. There are typically multiple rounds of dollars spent for associated tooling considering prototyping, production, and late redesigns due to findings making win-win scenarios for the business and suppliers more difficult (Figure 2).

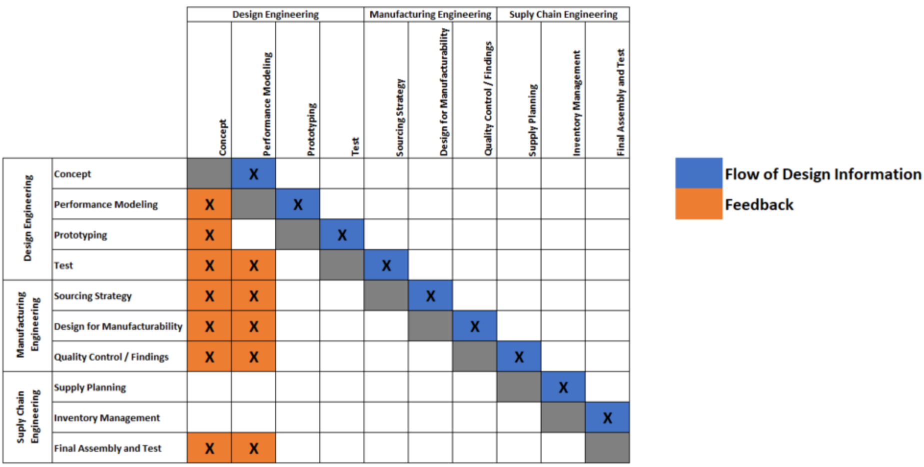

Figure 2. A high level Design Structure Matrix representing the traditional product development process.

3. Integrated Design, Manufacturing, and Sourcing Process

As access to compute resources have evolved, there is now access to manufacturing and design data that can be leveraged for new methods of generating new design concepts. A key driver of this is the idea of digital manufacturing where 3D modeling, can seemlessly be integrated with traditional modeling solution[4]. Structural, thermal, and manufacturing simulations can more closely simulate the part fit and function prior to building any aspect of the part. With the advent and adoption of these new technologies enginering teams can push the boundaries of engineering and physics along the arc of innovation. Firms that are quick to adopt new processes will inevitably be able to innovate more rapidly and with more confidence by iterating through variations on the designs using data to closely mimic and explore probablistic real world outcomes. Figure 3 identifies a potential framework for firms to adapt and integrate new efforts and technologies into their process to further innovation in design and manufacturing of complex systems while leveraging and evaluating new manufacturing techniques such as AM.

The concepts discussed are an attempt to bolster the tacit knowledge discussed in [1]. Tacit knowledge refers to the accumulated knowledge internal to an organization. This includes domain design expertise, the associated manufacturing opportunities and limitations. The goal of this section is to influence and attribute a growth mindset to this set of knowledge to increase this knowledge base to add to the organization's foundational knowledge by driving increased adoption of AM methods and promoting a more collaborative effort.

3D modeling is pervasive throughout most engineering firms and is widely adopted by most members of the organization. But recent advancement allowing for more compute resources at a lower cost 3D CAD and modeling platforms have become more feature-rich and are able to support design decisions in new and novel ways. While traditionally most CAD software allowed for designers and engineers to simply generate geometric data, the introduction of new features in these tools allows for more time to be spent in the design exploration phase of the development cycle as well as providing more data downstream in the development process. A few features that benefit the development process, include model-based definitions, manufacturability modeling based on standard equipment, carbon accounting, and feature based modeling combined with analysis software. These additions can address reliability concerns associated with traditional manufacturing as well as addressing the uncertainty in AM given its releatively nascent state.

To communicate part design in TM a 2D document that conveys the manufacturing specifications for the part in question using Geometric Dimensioning and Tolerancing (GD&T). This file is derived from, but separate from the 3D model the designer has been working with and requires the designer to translate considerations they have made onto a 2D medium. With model-based definitions the GD&T specifications are placed onto the 3D model and are inherent to the part itself allowing this data can be used downstream. The designer will be able to translate their design intent and constraints in real time for performance modelers and quality control down stream[5]. This allows the designer to communicate their GD&T with external manufacturing engineers and any future dimensional or tolerance changes will be incorporated in the new file they send without the need to update a secondary drawing file repeatedly. This data can be imported into measurement tools without the need for manual interpretation streamlining and possibly automating quality control without the need for tedious manual interpretation of 2D prints.

Once a concept is finalized the model can be imported into Finite Element Modeling (FEA) platforms such as ANSYS. FEA software has traditionally been used to model the part as designed from the 3D modeling software internal to the organization. As the AM industry continues to mature, there has been an effort to model the part to predict the geometry after the AM process earlier in the product development process to reduce or remove manufacturing findings. This allows the design team to validate that their part is going to be built correctly and then can use that model a realistic representation of the physical part in verification activities before the part is built. Modelers can leverage integrated feature based modeling tools such as SpaceClaim [6] to optimize the design of the part, rerunning their model to meet the desired performance and seamlessly share their insights with the designer digitally. Once the modeled part passes validation of the manufacturing process the model can be saved with its parameters and exported into a digital warehouse. Next this file can be versioned controlled to similar to a normal Product Lifecycle Management (PLM) system.

Once the part is committed to the digital warehouse the part can then be pulled by one of many production houses. The standardization of the 3D printing machines means that a properly calibrated machine with the same digital file can consistently create a part that meets the quality of what was modeled regardless of location. When a firm has in-house technology, they can prototype with "end-use" parts by printing and tuning the printer parameters in a way that is repeatable. This means that with AM technology and a network of AM production houses the part can be produced in strategic geographic regions that suits minimizing cost and time for procurement of the part. At this point the design for manufacturability feedback has been completed and only critical findings will be needed to force a revision of the design. Therefore, the major task at this point would be to establish quality control measures such as those found in the ISO9001 standard. This would include periodic sampling of the produced parts and measurements using metrology equipment such as a Coordinate Measuring Machines (CMM) or optical methods. The main point here is the abiliy to prototype with end use parts, rather than trying to mimic a hard tooled component during the tooling timeline only requiring feedback to the designer during verification test activities.

As the AM industry grows distributed print farms production volume can be distributed amongst regions. The manufacturing and export of the production parts can then be optimized using facility location operations model since the need for creating or moving dedicated tooling is not necessary. This minimizes cost and lead time, which can then be utilized for inventory management and order planning. The key enablement here is the ability to leverage a just in time manufacturing model that is not constrained by long lead times and minimum order quantities. This would allow facilities in geographies with high production rates to leverage unused capacity at other locations via distribution channels to meet demand that cannot be met at one location. More dynamic inventory management systems not only reduces the need for stocking a warehouse with parts, but also reduces the need to maintain capitalized tooling assets such as molds for casting, sheetmetal, or injection molding.

3.1. Analysis of the Integrated Process

This new method allows organizations to leverage new developments in digital technologies to help address some of the biggest hurdles in the product development process today while meeting technical and business goals. A lot of these technologies center around, and can support the enablement of AM while also enabling a more flexible model for elements of the TM process.

As software capability continues to grow, more aggressive users are now able to evaluate manufacturing processes without needing significant trade specific knowledge to influence their designs. The DSM of the new process is shown above which identifies a reduction the number of feedback cycles. The bulk of the feedback remains in the Design Engineering phase of the development cycle while feedback outside of this process results at the end of the Manufacturing and Supply Chain engineering phases as verification activities (Figure 3).

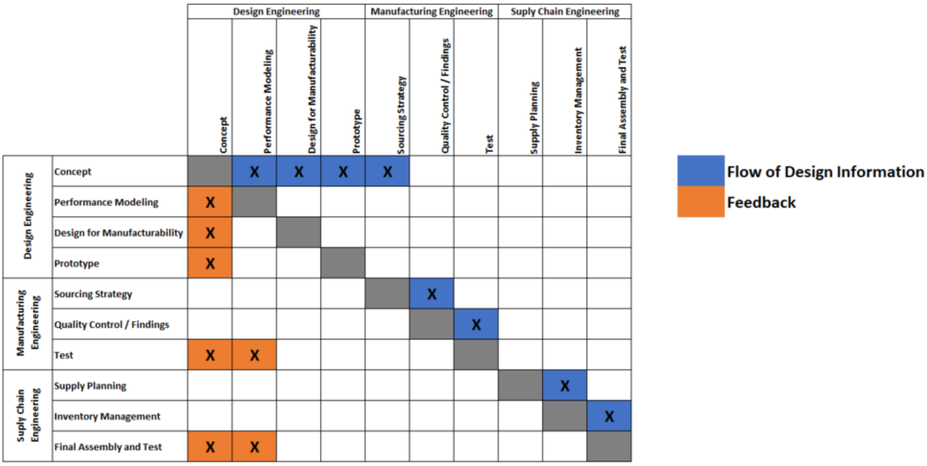

Figure 3. A high level Design Structure Matrix representing an integrated design process resulting in fewer feedback loops in the bottom left triangle of the matrix.

Increasing the access and amount of information in the design files further reduces the amount of churn downstream in the design cycle by allowing designs to be evaluated by multiple subject matter experts, both technical and non-technical, during the design process. By providing critical requirements that are easily accessible and tightly coupled to the released deisgn file any future updates are easily updated and shared across groups reducing delays associated with feedback loops. This allows flexibility for the design engineering teams to update products as well as allows the supply chain professionals to react to external events without affecting the technical aspects of the design like material specifications, GD&T, and design intent. Prototyping with “end-use” parts allows manufacturing to be independant of the design process and focused on quality control capabilities, production technology (printer brand or technology), and a global supply chain strategy to optmizes time and cost.

4. Integrated Process Implementation

The part selection process was executed via a Design for Additive Manufacturing Brainstorm session that included cross-functional representation from Design, Manufacturing, and Supply Chain and generally followed the framework from the sociotechnical model of adoption [1].The brainstorming session was divided into 3 parts. The first session focused on brainstorming using a modified SWOT analysis that leveraged a 2x2 matrix. The top two labels were meant to group parts by Capital Intensive Traditional Manufacturing, and Low Volume Additive Manufacturing Candidates. These labels were agreed upon organically by the team and the criteria for each category was negotiated. Capital Intensive Traditional Manufacturing was established to be parts that required greater than $250k in tooling investment. Low Volume Additive Manufacturing Candidates were established to be parts that had a quantity of 2-3 for an entire system, and plastic parts with long lead times during early user hardware.

Subsequently, the parts brainstormed in this session were then critically reviewed and ranked according to the team's perceived viability. This activity required the team to evaluate the parts based on the design, manufacturing (part production and final assembly), and sourcing strategies relative to business goals reducing capital expenditure. This acitivity required the cross-functional team to evaluate tradeoffs and establish an understanding of the part from all three mentioned perspectives. This was found to significantly drive discussions and AM knowledge development and sharing of insights which increased understanding of the deisgn intent, manufacturing constraints, as well as sourcing implications not normally found in the TM design process.

The last session was focused on the various concerns that were generated during the critical review and ranking process. In this session the team was tasked with addressing the concerns for each part with actionable items. The included analyzing the integrated process from beginning to end and determine what resources can be leveraged to overcome any perceived risk in the development process.

The team specified 3 different parts as the first candidates for this process. The team has begun the implementation of the 3D design technologies which includes the implementation of non-traditional 3D modeling approaches such as model based GD&T to be integrated into our quality control processes by our Procurement Quality Enginering (PQE) Team.

ANSYS Additive Suite was employed sucessfully to simulate the AM of the part. The manufacturing process displayed slight warpage during the manufacture of the part but did not allude to any degredation in the intended function of the part (Figure 4).

The part was printed using Direct Metal Laser Sintering (DMLS) technology and then scanned for dimensional characterization. It was seen that the warpage discovered in the finite element model was significantly correlated to the printed part. Scanning Electron Microscope and Electron Backscatter Diffraction was then used to explore the porosity of the metal parts to understand voiding in the material which could be modeled to understand failure modes for this novel process. The anlaysis resulted in a similar metallic structure to a TM part. The part was then functionally tested under load in a fixture that would replicate the functional application of the part and showed no significant performance difference between the TM version of the same part.

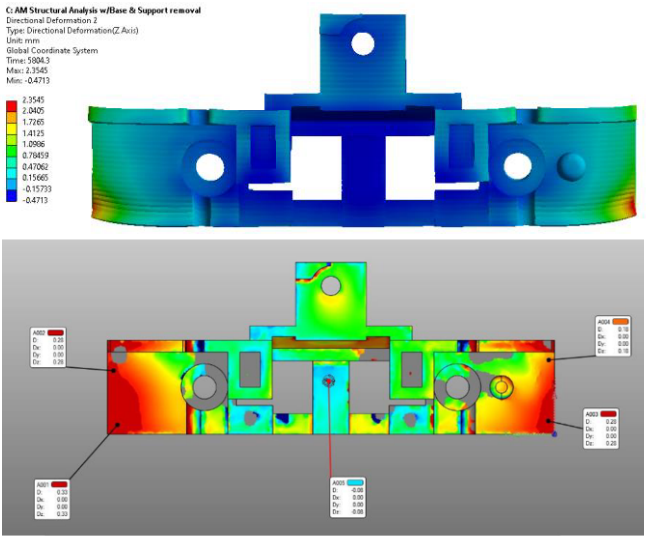

Figure 4. Simulation of AM process using ANSYS (Top). Laser scan of the actual 3D printed part (Bottom).

The team has identified production partners with geographically diverse facilities and are currently leveraging this work to build a model for quality control and supply assurance for a full production simulation implementation to capture the risks and limitations of implementation of this process leveraging new digital technologies.

At a high level, the process proved viable and set the tone for cross-functional, technical and non-technical consideration during the design phase and influenced increased attention to AM and other digital technologies. The process was agreed upon by Design, Manufacturing, and Supply Chain teams and facilitated a repeatable and robust initial framework to integrate AM into the supply chain for low to mid volume production. The bulk of the work done was to mitigate concerns with respect to the uncertainty and lack of experience with new manufacturing technologies and processes.

5. Discussion

During the AM workshops several key concerns were addressed by the cross-functional team. Specifically, understanding of the AM process, special processes needed to establish part validation, and adopting a new perspective on the financial implications associated with AM parts.

Traditional manufacturing methods require an understanding of the process being leveraged known as Design for Manufacturability. This includes understanding of draft angles and parting lines for castings, minimum wall thickness for injection molded parts, and limitations for machined part features dependant on tool capabilities. Similar considerations needed to be made for AM where Design for Additive Manufacturing (DfAM) is a key element of tacit knowledge for any organization to fold into their organization. This includes the opportunities and limitations of various technologies such as Direct Metal Laser Sintering (DMLS), Digital Light Synthesis (DLS), or the common Fused Deposition Modeling (FDM). Each technology, similar to each manufacturing method, requires an understanding of the manufacturing process and it has been found that an educational series directed at the main AM technologies has been an effective way to disseminate this knowledge.

Because of the nascent nature of AM adoption, there is still uncertainty about the functional risks and repeatability of the manufacturing process. Therefore, nuanced functional testing and quality control processes are needed to validate the performance of AM parts. This requires futher understanding of various AM technologies and their functional characteristics. This too can be addressed with educational series, as well as leveraging an understanding of Wright's Law where learning by doing facilitates movement up the learning curve.

Not all parts are financially suitable for the AM process due to the fact that TM still dominates high volume production. But, when it comes to lower volume parts AM can save on capital expenditure by reducing the need for capital intensive tooling and adherence to MoQs. Organizations have begun addressing this by creating financial analysis tools that would compare a single part produce by TM versus AM using historical data. This will be a key component in the sourcing process.

With the introduction of the previously stated digital technologies, increased adoption, and other potential innovations the integrated development process will continue to evolve and drive further collaboration between various functional groups. Leveraging innovation in manufacturing whether it be IoT upgrades to TM or utilization of AM technologies, the arc of innovation will continue to pushed past it's boundaries. New design methods can be introduced at volume such as organic structures derived from Structural or Thermal Topology Optimization along with new material capabilities such as multi-material manufacturing to enable material characterstics specific to application. Furthermore, maturing of the AM technology allows for the electrification of the manufacturing process. This could allow organizations to reduce their environmental impact and establish geographically convenient suppliers that leverage renewable energy technologies while still providing the cost savings found in low cost manufacturing geographies.

References

[1] S.H. Chang, B.R. Moser, 3D Printing Technology Insertion: Sociotechnical Barriers to Adoption. *2016 International Solid Freeform Fabrication Symposium*, https://repositories.lib.utexas.edu/handle/2152/89743, accessed June 20, 2022.

[2] U.M. Dilberoglu, B. Gharehpapagh, U. Yaman, M. Dolen The Role of Additive Manufacturing in the Era of Industry 4.0. Procedia Manufacturing, 2017, Vol. 11:545–554. doi:10.1016/J.PROMFG.2017.07.148.

[3] J. Butt, Exploring the Interrelationship between Additive Manufacturing and Industry 4.0. *Designs* 2020, Vol. 4, Page 13. 2020 doi:10.3390/DESIGNS4020013.

[4] Additive Suite | Comprehensive Additive Manufacturing Solution. https://www.ansys.com/products/additive/ansys-additive-suite, accessed June 13, 2022.

[5] CETOL 6σ Tolerance Analysis Software Solution by Sigmetrix. https://www.sigmetrix.com/products/cetol-tolerance-analysis-software/, accessed Jun 13, 2022.

[6] Ansys SpaceClaim | 3D CAD Modeling Software. https://www.ansys.com/products/3d-design/ansys-spaceclaim, accessed Jun 13, 2022.