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A comparison of traditional manufacturing vs additive manufacturing, the best method for the job

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Abstract

Manufacturing industries and investors are always seeking to improve techniques to lower cost, energy and expand their capability. Additive manufacturing, started in the 1960s, has since had a rapid and continuous growth, bringing to light novel techniques to expand manufacturing capability and reinvent the wheel. At this stage, research and industry interest lie in determining where AM can replace or create new manufacturing systems. Traditional manufacturing refers to subtractive and long-established manufacturing methods, quality assured and implemented in the commercial space.

This paper reviews the capability of AM and its current development to compete or add to established traditional manufacturing regions. Literature reveals the capability of AM to fit into established manufacturing regions for low and high production volume products. The paper comparison focuses on the similarities, differences, advantages and disadvantages found in AM vs SM studying the economic and quality management status of the industry today.

Keywords: Manufacturing, AM vs Traditional Manufacturing, Defects in Manufacturing, Quality Assurance Progression, Manufacturing Regions for AM, Part Characterization

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1. Introduction

The rapid proliferation of Additive Manufacturing (AM) in the last 50 years has seen the developing manufacturing sector integrated into design and modelling as a rapid prototyping technique [1]. AM better known by the buzzword '3D printing', uses revolutionary technology to create complex shapes building a part up layer by layer. Contrary to established Traditional (Subtractive Manufacturing (SM) and Formative Manufacturing) techniques, whereby material is either removed via machining, drilling or grinding techniques or casted into molds, AM has a higher level of design freedom [2]. The ability to fabricate complex parts in one machine and job, has businesses determined to establish AM as a certified end-user product manufacturing technique. AM research and company integration of the technologies has progressed AM from rapid prototyping to rapid tooling and now to a future in Direct Manufacturing [3]. However, Business and Manufacturers are divided on whether AM will reach this goal. High value, low volume manufacturing industries such as Aerospace, have companies such as General Electric (GE) Aviation predicting a new line of over 100,000 additive parts by 2020. Alternatively, mass manufacturing industries such as the Foxconn Technology Group, feel "3D printing is a gimmick", despite 30 years of working with AM technologies [2].

AM has integrated numerous manufacturing techniques (powder bed fusion, directed energy deposition, material extrusion, binder jetting, curing, lamination etc.), to develop an extensive range of technologies of potential interest to industry [1]. Several comprehensive AM technology reviews have been documented in previous works for further explanation [4-7]. The drive behind the rapid advancement of AM technologies is due to the research focus on developing low cost machines, increased material variability, and the complexity advantage to cater to a wide range of applications. New strategies and technologies combine multiple materials (including hard plastic and elastomers) within a print.

The design freedom offered by AM has its advantages and disadvantages from an industry perspective. Skepticism is shown to the lack of fundamental design guidelines for most AM technologies, where currently, recommended design optimization is offered by AM manufacturers or software. There are few professionally trained of the former and a high expenditure in employing the latter. The ability to produce complex geometries, difficult to achieve utilizing material removal methods, make it unnecessary for AM to follow the traditional design for manufacturing and assembly (DFM/DFA) principles [8]. Instead, AM falls under its own manufacturing design regulations, design for additive manufacturing (DFAM) [9-11], though arguments have been made that it should instead be considered manufacturing for design [12]. However, standardization and establishment of DFAM principles is still progressing and requires more work. Additionally, the absent standardization of best practices, has slowed the development of Quality Assurance (QA) and Quality Control (QC) strategies to progress industrial certification of AM manufacturing. In some cases, the problem lies with the unpredictability of the machine to perform, introduce defects into the printed part and difference in surface roughness across prints for the same digital input [1]. Where SM produces machined components with high precision, low complexity, AM trades geometric complexity for poor tolerance and relative quality [13].

The aim of this paper is to review where AM technologies dominate SM in established manufacturing regions. Previous works, such as that of Connor et al [2] have determined the types of AM products that can fit into established manufacturing regions based on three contributing factors; customization, complexity advantage and volume. The three over-running manufacturing regions can be summarized as Mass Manufacturing, Manufacturing of the few and Customized for the Individual. However, there are key factors contributing the slow penetration of AM into the commercial market, rapid prototyping capability aside. These keys factors are namely the QA/QC methods or standards, and economic strategies. The sections in this paper reviews and discusses the similarities, differences, advantages and disadvantages found in AM vs SM through a compacted analysis of documented works for these key factors.

2. Manufacturing Regions

Manufacturing regions can be categorically classified and defined by three key attributes; Complexity advantage, Customization and Volume. Complexity advantage is the final geometric complexity and feature location a manufacturing method can achieve. Customization, is focused on the ease of feature and individualistic variability the manufacturing technology offers that makes a similar product unique to each other with a customizable feature [14]. Volume refers to the production quantity of parts in an order or batch, whereby the production volume can range from singular to multiple parts. Following its rapid advancement, the focus of AM has moved from rapid prototyping, to rapid tooling and manufacturing. Several factors contribute to the selection of a manufacturing method; cost, part complexity, material usage and material property requirements, time, energy consumption, sustainability and so on. The Wohler's 2013 Report provides an extensive overview of AM's integration into the industrial market [15]. The following sub-sections study the degree of volume, complexity and customization has on an AM product vs a traditionally manufactured product. Notably, where AM can dominate SM, or alternatively cannot compete with conventional methods.

High Production Volume Based Manufacturing: Mass Manufacturing, Mass Complexity and Mass Customization

Lost cost high volume production has been the primary focus of traditional manufacturing industries. Discussed further in section 3.1, the economic advantage of this region has enabled low-wage countries to optimize their manufacturing capability [16]. This is especially true for Mass Manufacturing; parts characterized by their simplicity and lack of customizability. The high capital investment required to create assembly and production lines using AM, does not make it a financially feasible investment for manufacturers [17]. Conventional methods such as injection molding still dominate this space. The complexity advantage offered by AM, has provided opportunities to essentially 'hit two birds with one stone' with the ability to eliminate forging, and joining process by printing complete parts in one print. An example of this is the metal acetabular cup [18] used in hip replacement surgeries, where nearly 440,000 hip replacement surgeries are performed in the U.S. alone [19]. The cup is one part of the implant inserted into the hip, previously manufactured using numerous SM and formative manufacturing methods (forging, machining, coating etc). An AM powder-bed fusion metal printer, can build the acetabular cup, and add the porous surface into the surface layers in a single print. Production of this product falls within the Mass Complexity category, where parts exhibit complex geometries, without customization features. The medical industry has capitalized on this manufacturing region for implants and protheses through the replication of translated scans (x-ray, CT and MRI) [20]. The third high volume-based manufacturing region is Mass Customization, defined by its ability to provide individually designed products and services to every customer through high process agility, flexibility and integration [21-23]. An agile and quick approach to changes is a key characteristic companies are after, in order to stay ahead of the market with innovation and competition [14]. The absence of lead time and quick design adaptation in AM, with unique characterization provided by 3D scanning, sets AM ahead of conventional manufacturing methods for this region. Popularly known products now produced through a mass customization manufacturing model include, Invisalign brace molds by Align Technologies using AM Stereolithography printers [24], with nearly 17.2 million braces created in 2012 alone. Reeves et al [25] documents other instances of mass customization of AM and details associated the financial and manufacturing model for hearing aids [2], phones cases [2], computers etc.

Low Production Volume manufacturing – Complexity for free with AM

This region refers to low-volume (numerically unique for each product type) production of products. The product manufactured by conventional methods will generally have limited complexity and customization (the manufacturer might offer minor variations for customer preference), however with AM manufacturers can achieve a high degree of complexity for the same cost. Low volume is defined specific to the industry, product and sale capacity [2]. The introduction of AM into the manufacturing sector began with low volume production for rapid prototyping, with Stereolithography. Functional assembly manufacturing is still the primary use of AM according to the Wohler's report [15]. However, investors are now interested in direct part manufacturing, particularly aerospace, automotive and rapid tooling industries. Hopkinson and Dickens et al [26], provide a successful cost model to illustrate the breakeven point of AM vs SM for volume. The study examined the cost of fabricating a small plastic lever using AM powder bed fusion vs conventional injection molding manufacturing. The study concluded for a production volume smaller than 10,000, AM had a reduced unit cost compared to injection molding [27]. While SM dominates the Mass Manufacturing region financially, AM is better suited to fabricate tooling and fixtures required for conventional Mass Manufacturing molds [28, 29]. AM offers a reduced lead-time and cost to capitalize on high value, low production of parts such as those used in ships, automation, aviation, satellites etc. This concept is known as Rapid Tooling, referring to tools able to form several thousand or even millions of parts before wearing-out. Levy et al [29] provides a summary of direct and indirect AM technologies used for rapid tooling.. AM also offers manufacturers the ability to trade complexity for customizability in low volume production, where AM is being used for individually customized repair parts [30].

Andrew et al [31] provides a concise illustration to summarize the relationship between the factors. The conclusion to be drawn, is that production volume is an independently important factor, whilst customization and complexity are interchangeable in terms of impact.

3. Economic Strategies: The financial overview and societal impact

The economic impact a manufacturing strategy has financially and societally, can determine the areas of success or advancement for businesses to pursue. This is particularly true for those countries seeking to further their manufacturing specialty to shine after the major success low impact countries have had with mass manufacturing. Studies conclude that AM would best dominate the low production-manufacturing sector for its customizability, short lead-time and complex geometric capability. Petrick et al [32] studies the disruption in manufacturing caused by the new manufacturing and design opportunities offered by AM. The paper examines the economic status quo surrounding AM, including the established and reformed finance/economic models that support different AM technologies currently. Previously companies have monopolized on the successful method of reducing variability in design, to maximize on the repetitive production of interchangeable parts, following the DFM advantage offered by traditional manufacturing methods dating back to the 1990s [33, 34]. DFM set designers and manufacturers to follow a set of rules, limiting creative expression and instead encouraged cost-effective production. This created the 'design-build-deliver' model, from which companies have attained high-quality products at a reduced price, with higher success. The rapid improvement in transportation caused by the introduction and advancement of digital technologies, brought low-wage countries, such as China, onto the world stage of competitive manufacturing.

Alternatively, AM offers flexibility which enables manufacturers to create an optimal design for lean production [35]. AM has created the opportunity for supply chain simplification and has been successfully been implemented for 'single unit and very low-volume production' in several sectors. These sectors range from the highest implementer of metallic AM Aerospace products [36], to plastic FDM printed AM prosthetics [37], customized for the individual hearing aids [32], medical implants [20] and brace molds [2], unique complex patterned art and fashion.

AM machines offer production flexibility; the machines do not require expensive set-up arrangements, making the technology economical for smaller batch production [8]. However, AM is still a considerably expensive investment compared to traditional manufacturing machines [38]. Entry level printers begin at around US$150, these are rudimentary small bed FDM prototyping personal use printers [39]. However, production level printers can range from US$5,000 to near US$1,000,000 [40]. Machine purchase aside, material cost varies for polymers, elastomers, and even metallic feedstock (powder, resin, wire, sheets). Additionally, running costs for the machine, and gas used for AM machines requiring an inerted environment and several other contributing costs add to the high expense of the process.

The National Institute of Standards and Technology (NIST), U.S. Department of Commerce, present a comprehensive summary of cost analysis and cost effectiveness in AM technologies [41]. To summarize, the review states AM is cost effective for low-volume/small batch manufacturing with continued centralized manufacturing rather than distributed manufacturing. Currently, research models conclude that while there is an expensive initial investment for machine and personal costs, distributed production (close proximity to the site of use), is not a viable option for AM. However, should AM develop into a widely adopted process with increased automation and reduced machine costs, distributed production may become more feasible.

To achieve the dominating potential AM has over SM in extended life, reduce lead time, labor and natural resources, e.g. make automobiles lighter to reduce fuel costs or produce combustion engines to reduce cooling needs, several factors need to be analyzed. There is a need to keep account of the natural resources, labor and time expended on production, utilization, disposal and utility gained from new designs. The difficulty in quantifying and documenting these factors, stagnates the progress of AM.

4. Quality Assurance and Quality Control for AM vs SM

Precision manufacturing and standardization of products are dependent on Quality Assurance (QA) and Quality Control (QC) standards and procedures [42]. A major risk and fear with the flexibility or 'print a fix at home' manufacturing AM offers, is that a product will be used that is not fit for purpose [1]. The complex geometry, internal lattice structure, surface finish, layer orientation and topology optimization, all contribute to the mechanical aptitude of an AM part. In cases where powdered material is inserted into parts, careful design optimization is required to determine how is can be extracted. Loose powder within the part could not only be considered a health and safety concern but also impact the mechanical and structural integrity [43]. The vast capability of AM, referring to material variety and manufacturing process differentiation, has resulted in multifaceted quality requirements and standards. For this reason, SM continues to dominate AM in quality, precision and reliability [13]. In turn, the inconsistency and complexity of each AM system has made it a challenge to develop a standard set of rules causing a slow development of Quality Assurance (QA) strategies. Quality is quantified and qualified differently depending on the part produced. The degree of quality required is often dependent on the risk related to health and safety assurances required. For instance, a model toy plane would have an extremely low risk in comparison to a hinge printed for a commercial aircraft. Furthermore, each AM printer requires calibration and customization of the printer parameters, sometimes specific to certain types of builds.

The size, orientation, sharpness and location (within joints, exterior surfaces or critical sections of the structure) of defects within an AM part can impact the mechanical properties negatively. This is no different for SM manufacturing, in fact the type of defects is almost similar; porosity, cracks, inclusions, voids, balling, rough surface finish [44-47]. However, in AM aside from geometric imperfections, volume mismatch, layer removal and undesirable internal surface finish are issues that cannot be detected through typical mechanical tests. In SM batch testing is predominantly the most used QA/QC technique, where one test piece within a batch can be mechanically tested (i.e. tensile and compression tested), as a reflection of the mechanical properties for the remaining parts within that batch. While some AM manufacturers attempt to use a similar method for each print (can have multiple parts in one print in a big enough bed size), there have been concerns surrounding the impact of layer orientation, heat affected zones and inconsistent defect introduction that indicate batch testing cannot be applied to AM. Certification is usually achieved through repeatability and reliability of a manufacturing technology. An AM system has more dependent variables than SM, as detailed in the following paragraph below. However, despite the lack of AM standards, traditional standards commonly used in other manufacturing processes or materials have been applied to select AM printers/products by conforming to set parameters for individual machines (i.e. laser power, scan speed, powder spread etc.). Ensuring the use of quality tested powder/wire feedstock is important, inconsistencies in the particle size, wire/filament diameter, sheet thickness can impact the structural integrity with the wrong machine parameters. Lloyds Register and TWI Ltd have developed a document detailing the process for AM certification [48]. The guidelines were developed following traditional certification process standards, with the allowance of independent testing to be done by the industry/company specific to certain test cases. This approach is not always suitable nor efficient for AM technologies [49]. The reason for this is the intricate system that makes up an AM machine, unlike traditional calibrated machinery, AM does not always ensure the repeatability or reliability required for precision manufacturing. The four main contributing factors of concern in AM quality are the feedstock characteristics, the build environment, melt pool monitoring and build characteristics [47]. The need for new standards has been acknowledged by industry, research centers and academia, dating back several years with numerous surveys having been carried out [50]. Gausemeier et al [3] states certification processes customized to suit AM are a key success factor for the future of the AM industry. In 2009, the ASTM Committee F42 was formed for Additive Manufacturing Technologies, consisting of approximately 100 members (experts predominantly from USA and Europe). Following this, in 2011 the ISO Committee TC 261 for Additive Manufacturing was established. The AM board has developed strategies [51] for quality inspecting individual aspects of an AM process through the use of the following test methods; Chemical analysis, Mechanical Testing, Performance Evaluation, Metallurgical Analysis, Powders Evaluation and Non-Destructive Testing (NDT) [52]. NDT testing is currently a major R&D area, with companies such as EOS and ARCAM developing in-situ monitoring system for NDT quality assurance [6]. However, in regards to NDT testing, there is still a great deal of work to be done to achieve a life time Structural Health Monitoring (SHM) [53] system for AM machines. Sharratt et al [47] details a comprehensive review of NDT techniques for the qualification of AM parts and processes, required in order to developed an SHM system and the importance/need for it. Namely that the four contributing factors to AM quality mentioned previously, require further research to wholly certify each AM process. This is especially significant moving forward for those products with a higher risk, dependent on a fatigue load or fracture resistance.

Another major area mentioned previously in section 3.1 is the advancement of computational software for modelling and simulation, to determine mechanical stresses in a AM part based on parameter selection. Engineers are interested in using a computational approach, for AM build planning, to solve the Multiphysics process of AM [54]. To produce a complete representative simulation however, including a wide range of time and length scales, researchers claim that more than 130 variables need to be considered. The complexity of such a system, means most computational models would be run in high performance computing facilities only. Simplified computational software exists, but the investment cost is too high for most small businesses to consider using. Presently, more sophisticated models of AM processes can be found at the US National Laboratories, a company possessing immense computing capabilities [55].

Key requirements for the penetration of AM in the future into the wider commercial market, include high process stability, a database containing properties of AM-materials, On-line quality control processes, continuous certification and provision of design rules [3]. Furthermore, material heterogeneity and structural reliability are also essential factors to consider. It is clear the impact of risk mitigation that a product's quality needs to assure has a huge influence on the level of QA required. To ensure manufacturers neither underprepare or over-invest in QA technologies it is important to evaluate the level of QA required for each part printed utilizing AM technologies [54].

5. Conclusion

This paper reviewed the capability of AM and its current development to compete or add to established traditional manufacturing technologies. These regions primarily focused on the effect of production volume, customizability and complexity to determine whether AM or conventional manufacturing methods on a product type to be fit for purpose. It was concluded that current cost models for high production volumes are better suited for tradition manufacturing methods, however the higher the complexity or customization required AM is better suited. Production volume is an independently important factor, whilst customization and complexity are interchangeable in terms of impact. The paper comparison also focused on the similarities, differences, advantages and disadvantages found in AM vs SM studying the economic, environmental and quality management status of the industry today. AM offers flexibility, which enables manufacturers to create an optimal design for lean production. AM has created the opportunity for supply chain simplification and has been successfully been implemented for 'single unit and very low-volume production' in several sectors. AM machines offer production flexibility but is still a considerably expensive investment compared to traditional manufacturing machines. AM is cost effective for low-volume/small batch manufacturing with continued centralized manufacturing rather than distributed manufacturing. The clear advantage for AM vs SM, in terms of environmental impact, is the reduced wastage of material and resource efficiency. Key requirements for the penetration of AM in the future into the wider commercial market, include high process stability, a database containing properties of AM-materials, On-line quality control processes, continuous certification and provision of design rules. To ensure manufacturers neither underprepare nor over-invest in QA technologies it is important to evaluate the level of QA required for each part printed utilizing AM technologies.

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