Candidate Part Selection Methodology for Additive Manufacturing
## Titan Industries

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Introduction to Additive Manufacturing

Many companies are not familiar with additive manufacturing (AM) since the technology is relatively new. It is seen as a tool to possibly increase their innovation potential, but the capabilities, limitations, and economic factors of the technology are often misunderstood. Selecting appropriate parts for fabrication by AM is hindered by this lack of knowledge and a lack of appropriate design rules for the proper use of AM. To assist in selecting parts that are candidates for AM technology, both technically & economically, a methodology has been developed.

This document reviews the process and characteristics of electron beam melting (EBM) additive manufacturing. It is important to consider the physical mechanisms occurring in this process to understand the capabilities, limitations, and economic factors associated with EBM AM. After the review of the technology, these factors are discussed in detail. Following the discussion of the technical and economic aspects of the technology, a candidate part selection methodology is presented that utilizes these factors to determine which parts will most likely benefit from production by EBM AM.

Electron Beam Melting Additive Manufacturing

Additive manufacturing (AM), is a maturing technology where physical solids parts are constructed layer-by-layer. These parts are made directly from electronic data, generally files from computer-aided design (CAD) software. This group of technologies offers many design and manufacturing advantages such as short lead-time, complex geometry capability, and the elimination of tooling.

Similar to electron-beam welding, electron beam melting (EBM) utilizes a high-energy electron beam as a moving heat source, to melt and fuse metal powder to produce parts in a layer-building fashion. EBM is one of a few AM technologies capable of making full density functional metallic parts, which drastically extends AM applications. The ability to directly fabricate metallic parts can significantly accelerate product designs and developments in a wide variety of applications. This is especially evident for complex components that are difficult to produce by conventional manufacturing means.

This technology has attracted increased interest from different industries in recent years, due to its unique characteristics, including: high-energy efficiency, high scan speed, and moderate operational cost. When compared to using a laser as the thermal source, the use of an electron beam offers extensive features such as higher build rates due to increased penetration depths and rapid scanning speeds. Many research groups have been studying the EBM technology from different aspects and for various applications.

Process Principle

A conceptual schematic of an EBM machine is shown in Figure 1. The principle of the technology is similar to that of a scanning electron microscope. A heated cathode in the upper
column emits electrons, which are collimated and accelerated to a kinetic energy of about 60 keV. The electron beam is controlled by two magnetic coils, which are housed in the lower column. The first one is a magnetic lens, which focuses the beam to the desired diameter, and the second one deflects the focused beam to the desired point on a build platform. The electron beam gun itself is fixed. No moving mechanical parts are involved in beam deflections. In the chamber of the middle part of the machine, fine metal powder, on the order of 45 – 105 µm, is supplied from two hoppers and forms a thin layer by a raking mechanism before each layer build. The typical layer thickness for the Q20 model is approximately 90 µm.

The computer controlled electron beam scans over the powder layer in a predefined pattern and consolidates the desired areas into solid and dense metals. The beam has to first scan at a high speed (order of 10 m/s) in multiple passes to preheat powder to a sintered state, while a beam scan on the order of ~0.5 m/s is used during the melting cycle. After the melting cycle, a new powder layer is laid on top and the scanning process is repeated until all layers are completed.

The entire process takes place under a high vacuum. During the melting process, a low pressure of inert helium gas is added to the vacuum chamber to avoid build-up of electrical charges in powder. When all layers have been completed, the built part is allowed to cool inside the process chamber, which is then filled up with helium as to assist cooling.

Applications and Challenges

EBM’s unique capabilities are especially beneficial to the aerospace industry; creating new opportunities for both prototyping and low volume productions. The time, cost, and challenges of traditional manufacturing are eliminated, which makes the components readily available for functional testing or installation on a system. Additionally, the additive process opens a door to new design configurations and weight-reduction alternatives.

The energy density of the electron beam is high enough to melt a wide variety of metals and alloys. EBM processes have the potential to work with many material classes including aluminum alloys, tool steel, and cobalt-based superalloys. However, titanium alloys, in particular, Ti-6Al-4V, were the first material extensively researched and widely used in EBM technologies. Using Ti-6Al-4V with EBM is a desirable since the manufacture of highly complex and functional titanium alloy parts is difficult using traditional processes and the material offers superior properties: low density, high mechanical strengths, corrosion resistance, human allergic response, and good biocompatibility.

Powder Characteristics

Raw Powder

Raw materials used in EBM are metallic particles from powder metallurgy, and the characteristics and quality of powder strongly affect the process performance. The powder morphology an important factor in the EBM process. The powder morphology affects flowability, powder packing, and ultimately, heat transfer process phenomena. The powder used in EBM is spherical in shape. The spherical shape may contribute to improved flowability, and thus, may ensure high build rates and part accuracy.

In general, fine powder is used in EBM. The powder size distribution also has a significant effect on the build part density, surface finish and mechanical properties. Spherical diameter of the powder ranges from 45 – 105 µm. For the chemical composition, Ti-6Al-4V powder used in EBM has a nominal composition and is comparable to the common Ti-6Al-4V specification.

Sintered Powder

The thermal cycle in EBM, which includes preheating, subsequent melting, and solidification, is critical to determine the microstructure and mechanical properties of the EBM parts. Different from the laser additive manufacturing process, the EBM process applies the preheating to lightly sinter the precursor powder layer by using electron beam at a low power and a high scanning speed.
The preheating process serves two purposes: holding the metal powder in place during the subsequent melting scan and reducing the thermal gradient in the build part. The sintering mechanism is that small particles partially or completely melt. Sintering plays an important role as a binder to bond the majority of large particles together, which will not only hold the particles and withstanding the impact from electrons, but also prevent the spheroidization effect in the part surface. The preheating process contributes to the metallurgical bonds and partial melting of the powder.

**Microstructures**

The microstructure of Ti-6Al-4V samples from EBM have been studied extensively in universities. The samples show an ordered lamellar microstructure, consisting of extremely fine grains, as can be expected by the thermal characteristics of the EBM process: small melt pool and rapid cooling. EBM components possess a columnar shaped morphology of the prior β phase with a growing direction parallel to the build direction, which is a consequence of primary thermal gradients that exist in the build direction.

Gas voids or porosities are typical defects in EBM parts. It has been shown that porosity defects due to gas voids in built samples can be largely eliminated by a single standard HIP cycle, but remnants sometimes persist. In addition, some gas bubbles are produced from recycled powder and stay in EBM-built parts. It is essentially impossible to eliminate the intrinsic gas bubbles in EBM parts because of the melt and liquid phase surface tension and the low gas pressure. However, because of the small void size (order of 10 µm), they may not impact the mechanical properties of EBM-built parts.

Since EBM relies on selective solidification of the top powder, layer energy is inserted into the material in a non-uniform way. Large temperature gradients may emerge due to selective heating of powder areas and thus, residual stresses may be induced. If the residual stresses exceed the bonding abilities between layers, it results in delamination, which depends on the scanning strategy. Specifically, the orientation of the scan vectors has a considerable influence to delamination. It has been reported that operating parameters have significant effects on the part characteristics, quality consistency, and process performance.

Variations in melt scan, beam current, and scan speed affect the EBM built defects such as porosity, and may cause significant property-performance variations. In general, the beam power, diameter, and speed, as well as the pre-heat temperature are four major process parameters; the first three are tied to the thermal cycle variables, temperatures and cooling rates, and the pre-heat temperature governs the sintering state of powder prior to the melting scans.

**Mechanical Properties**

EBM part properties have been frequently investigated. Some studies indicated that properties of EBM parts are comparable to those from conventional processes (wrought). Other research has indicated improved hardness of EBM parts. Changes in local chemistry and different microstructures have been suggested as possible causes.

**Tensile Testing**

Tensile testing has been widely used to characterize the mechanical properties of EBM parts. Some researchers found that the ultimate tensile strength (UTS) of EBM built specimens is higher than the wrought or annealed ones, with a lower ductility. However, others presented that the UTS and ductility of the cast and wrought Ti-6Al-4V specimens were higher than those of EBM counterparts. The reason for the difference could be attributed to the variation in the build parameters, which result in different structures such as composition, structures, pore size, and porosity distribution.
Results have shown that UTS and yield strength (YS) decreased with the increase of energy input. However, the change in UTS (2% change) and YS (3% change) was small. Anisotropic behavior may be observed between the Z-axis and the X and Y axis. This is primarily caused by the difference in bonding between adjacent powder (X & Y axes) and layer to layer (Z-axis). Due to this, part orientation may affect the overall performance of the part. The anisotropic effect on the mechanical behavior of Ti-6Al-4V manufactured by EBM has been investigated. Tensile testing indicated that YS and UTS for flat-build samples have distinguishably higher values than those of the side-build and top-build samples.

**Compressive Strength**

Compressive testing has also been used to evaluate EBM parts, mainly for meshed, porous, or cellular structures in biomedical applications. The compressive test showed that a linear elastic deformation stage, followed by a long plateau stage with a nearly constant flow stress to large strains, in which cells collapse due to buckling and plastic yielding, and the final stage with the stress reaching the maximum value.

**Other Testing**

Other types of mechanical testing such as hardness tests and flexural tests have also been used in studying mechanical properties of titanium alloys processed by EBM. The hardness of EBM specimens were higher than that of the cast or wrought specimens. The Young’s modules and hardness are not significantly affected by the powder size or the layer thickness within the range of studied process parameters. However, the part surface appearance was noted to be different with the different powder sizes. The results of the flexure tests showed that the elastic properties of the structures are relatively consistent between builds.

**Geometric Attributes**

Even with impressive advantages over conventional manufacturing technologies, EBM still exhibits several process challenges, such as dimensional accuracy and surface finish. Despite an intense interest in attainable accuracy and strengths by EBM, few studies have emphasized the geometric aspects in EBM. The observed errors of EBM parts are significantly larger than those of typical machined parts by at least an order of magnitude. Errors of parts are often due to the process. Cyclic thermal effects, including deformations due to residual stresses, are most likely the cause.
Additive Manufacturing Limitations

While additive manufacturing enables capabilities unavailable with traditional manufacturing, the technology does have its limitations. As such, the technology is not suitable for all applications. AM is not capable and not useful to manufacture all imaginable parts. The limited size of the building chamber excludes many applications. Also, the as built surface quality and dimensional accuracy are often unacceptable for a parts requirements. The economical effort for post processing to achieve the requirements must be taken into account.

In this section, limitations are presented in the form of design constraints and economic and technical disadvantages. Design constraints need to be taken into account when choosing an application for the technology and in the design/redesign of parts. Economic and technical disadvantages must be considered in the strategic use of this technology.

Design Constraints

A brief overview of the design constraints for the Arcam Q20 system is presented below. A more comprehensive design guide for the Q20 is currently under development.

Build Volume

The Arcam Q20 has a build volume that is 350 mm (13.78") in diameter by 380 mm (14.96") high. Normally 2 mm (0.079") of grind stock is required to the bottom of the part that is connected to the start plate. This extra stock is required to eliminate interdiffusion between the titanium part and the stainless steel start plate, and should be accounted for in the build volume limitations.

Minimum As-Deposited Wall Thickness

In the Z direction the minimum as deposited wall thickness is recommended no less than 0.76 mm (0.03"). If thinner walls are required, they may be achieved by grinding off additional material.

Grind Stock

The as deposited surfaces is normally better than 700 microinch RA. Surface finish becomes rougher in regions where supports are necessary or with downward facing surfaces as they are supported in the powder.

In areas where a better surface finish is required, excess material must be added and post processing methods are used to meet requirements. A minimum of 0.5 mm (0.02") of grid stock is needed to achieve this, but 0.76 mm – 1.3 mm (0.03"- 0.05") of grid stock is recommended. As mentioned above 2 mm (0.079") of grind stock is required to the bottom that is in contact with the start plate to eliminate interdiffusion of the start plate with the part.

Minimum Hole Size

Due to steady state sintering that occurs during the manufacturing process, holes less than 1.3 mm (0.05") in diameter may close up during manufacturing. This phenomenon is more prevalent as the length to diameter (L/D) increases. Therefore for L/D > 10, the minimum recommended diameter is 2.5 mm (0.1").

Curvature for Internal Passages

The EBM system is a powder bed fusion process, thus powder removal must be considered in the design. This should be accounted for in designing curvature for internal passages. The greater the radius of curvature, the easier it is to remove the powder. A design guideline has not yet been quantified, but the powder removal difficulty is a function of the passage diameter and the length to diameter.
External features
Due to the steady state sintering that occurs during the manufacturing process, external features should be separated by a minimum of 2 mm (0.08”). Features closer than this may sinter together. Raised or indented external features should be at least 0.76 mm (0.03”) normal to the surface, 3.3 mm (0.13”) wide, with a thickness of at least 1.3 mm (0.05”).

Tolerances
The as deposited tolerances are +/- 0.4 mm (+/- 0.016”).

Post Processing Methods

Machining
Machining is the most expensive option to remove surface roughness, but necessary when tight tolerances and surface finish are required.

Grinding/Polishing
Grinding or polishing generally cost less than machining. Tight tolerances can be achieved (+/- 0.127 mm; +/- 0.005”) and a surface finish from rough to mirror may be obtained.

Tumbling
Tumbling/vibratory polishing is useful for removing sharp degrees. This is an inexpensive treatment and useful in many applications.

Chemical or Electrochemical Milling or Machining
This post processing process is more expensive than tumbling, but will allow the part to pass dye penetrant inspection. This process is beneficial for removing FOD or trapped powder from the rough surfaces. A surface finish of 125 RMS is possible with this method.

Abrasive Flow Machining
Abrasive flow machining pumps slurry with a ceramic to smooth hard to reach surfaces. Very high surface finishes (16 RMS or better) are obtainable with this process.

Joining
Electron beam or gas tungsten arc welding may be used to join Ti-6Al-4V parts.

Economic Disadvantages
Certain aspects of the additive manufacturing process lead to economic disadvantages. These are due to both the process of the technology and the infancy of the technology. It is important to understand these economic drawbacks in the candidate part selection process.

Build Time
The build chamber in the EBM system operates in a vacuum. As a consequence of this, the heat input from the electron beam is primarily transferred through the powder by conduction. This is advantageous since it reduces thermal gradients and thus reduces residual stresses. After the build process is complete, the powder bed contacts heat sinks and is allowed to cool. If oxygen is allowed inside the build chamber while the powder bed is still hot, the titanium powder will pick up oxygen content and become unusable.

Depending on the build, the Q20 system requires between 3 - 8 hours of ‘build overhead time.’ Prior to melting, the system must pull a vacuum to a sufficient level, and after the build it must be allowed to cool. To minimize the impact of the build overhead time, multiple parts should be built concurrently, since this is a batch process. The build overhead time must be taken into account with the relatively slow fabrication rate of metal additive manufacturing. The Q20 melts approximately 80 cm³/hr, which translates roughly to 7 mm/hr. Therefore, orientation and maximum dimensions of the part impact the total processing time. Currently, the technology is quite expensive and processing time are long. This translates into costly hourly rates to operate the equipment.
Limited & Expensive Materials

To obtain fully dense parts with minimal defects, the powdered metal must be of a certain shape and size. Additionally, the equipment must use the proper set of process parameters for satisfactory results. Development of a set of process parameters requires significant effort and time. As such, a limited number of materials are available for use in additive equipment. The process parameters for Ti-6Al-4V on the Q20 have been well established, and this is currently the only material Titan Industries offers for fabrication.

The raw material cost is driven up by the required powder specifications and the relatively low number of users. The low demand for the powder has kept some major suppliers from entering the market. This has driven up the cost of the raw powder. While some benefits are gained with the very low scrap rates with additive, high powder cost compared to wrought cost is economically disadvantageous.

Build Costs

Besides the hourly cost to operate the equipment and the expensive materials, additional costs are associated with additive. Each system has a certain set of consumables that must frequently be replaced. This includes heat shielding, start plates, and cathodes. As the additive process produces a near net shape, post processing costs must be accounted for as well. Depending on part requirements, a significant percentage of the total part cost could be due to post processing work. Process planning and following design for additive manufacturing principles can minimize these post processing costs.

Economies of Scale

Additive manufacturing technology does not have economies of scale. Since no fixtures or tooling is required to fabricate parts, the unit cost per part does not decrease as the quantity increases. This is advantageous for small quantities of parts, but becomes economically disadvantageous if the quantity is high enough. Breakeven points are highly dependent on the effort required to traditionally fabricate the part. In some cases designs may only be fabricated through additive methods, in which case, the breakeven point of quantity is not the main consideration, but rather, the ability to meet demand. Besides some minor cost reductions as the build volume is more efficiently utilized, the cost for the first part is roughly the same as the cost for the nth part.

Technical Disadvantages

Surface Roughness

Surface roughness of the as built part is caused from the elevated temperature of the powder bed and the finite size of the raw material powder. As the contours of the part are being melted, heat in the region causes steady state sintering to occur. This causes neighboring particles to sinter to the part and create roughness on the surface. While a relatively smooth surface is common with machining processes due to the nature of the process, unnecessary surface requirements on additively built parts can unnecessarily increase the cost.

Part Shrinkage

Since the EBM process involves fully melting powdered metal, part shrinkage may occur. Shrinkage is size reduction due to cooling and solidification of the metal. It is primarily a function of cooling rates and physical changes occurring due to the increase in the energy density when the powder material is sintered and solidified. Shrinkage depends on the layer thickness variation, directional cooling rates, and powder packing density.
**Dimensional Tolerance**

Dimensional tolerance is affected by the build orientation of the part. Since AM builds a part layer by layer, staircasing (noticeable step changes between layers) may be observed in the Z-axis. This creates a loss of dimensional tolerance due to the finite thickness of each melt layer. Part shrinkage due to the cooling of the part may also affect the dimensional tolerance. Distortion of features may be caused by variations in directional cooling. AM does not naturally lend itself to tight dimensional tolerances due to surface roughness from steady state sintering, staircasing, and part shrinkage. Therefore, tight tolerance requirements must be well justified in the design. Additional stock may be added to the part and later post processed to achieve tight tolerances, but this requires additional process planning and cost.

**Build Volume Constraints**

The build envelope for the Q20 is 350 mm (13.78") in diameter by 380 mm (14.96") high. The relatively small build volume limits the number and types of components that may be fabricated with AM. Even relatively small parts with one dimension exceeding the build volume may keep the part from being built additively. Large parts may be formed with joining techniques as discussed above, or with built-in fasteners, but the tradeoff is additional post processing work.

**Powder Removal**

The EBM process occurs in a powder bed. While this aspect of the process is beneficial in that the powder provides a level of mechanical support and a conduction path for thermal energy, the removal of the powder in the final part must be considered. While hollow parts may be built with the EBM process, holes must be placed in the surface in order to remove the powder. This powder is often semi-sintered and if the design contains narrow features and hard to reach cavities, removal of powder may be difficult.
Additive Manufacturing Capabilities

Geometric control with traditional manufacturing is limited by required clearance for tools, inability to access the inside of the work piece, and the need to develop tooling and fixtures. With traditional manufacturing, an increase in complexity leads to an increase in effort and cost. Additive manufacturing’s layer by layer fabrication allows for a high degree of geometric control, access inside the work piece, and elimination of tooling or fixtures. Increased complexity does not lead to an increase in the cost of the part. The greatest advantage of additive manufacturing is the high level of geometric and topology control, and the technical and economic benefits of this technology emerge from this capability. The technical advantages of additive manufacturing are discussed below.

Technical Advantages

Elimination of Tooling

The construction of tooling and fixtures in traditional manufacturing constitutes a significant expense. Traditionally, tooling cost must be amortized over a large quantity of parts to make manufacturing economically feasible. Tooling must also be stored in order to create replacement parts in the future. Process planning for additive manufacturing is greatly simplified since no tooling or fixtures are required. Tooling elimination allows for the economical mass customization of components and rapid design cycles. This feature also allows for a digital inventory of parts to be stored, which is beneficial for obsolescence issues.

Mass Customization

The geometric control of AM allows for the ability to customize individual parts on a mass scale. Since no tooling or fixtures are required to fabricate components, customized features are easily incorporated. The instructions for AM are contained within a digital model. The effort to customize a component lies in the creation of the input model in CAD, not in process planning for manufacturing.

Rapid Design Cycles

The time and cost associated with developing tooling for traditional manufacturing greatly impedes design cycles. Design changes are often difficult to implement once the tooling has been fabricated due to its cost. Often, the economic disadvantage to remake the tooling locks in the current design despite inefficiencies or flaws discovered during testing. Since this is not a factor with AM, rapid design cycles are allowed. Designs may quickly and economically be fabricated, tested, and redesigned with the AM process. This ability may lead to more efficient designs.

Reduction of Assemblies

As will be discussed in later sections, the ability to reduce assemblies into a single part creates both a technical and economic benefit. Technically, concatenating multiple parts into a single assembly leads to greater simplicity in the design and easier integration into higher assemblies. Economically, reducing assemblies has a positive impact on cost associated with the supply chain.

Functional Design

The geometric freedom of AM allows for designs to be shaped by the function of the part and not by the constraints of manufacturing. This is one of the greatest benefits of the geometric freedom, since improvement in the performance of the part can have a large impact on the lifecycle of the product. Function design includes utilizing optimization techniques to minimize or maximize an aspect of the part function within certain constraints.
**Topology Optimization**

Topology optimization is a numerical technique that utilizes finite element analysis to modify the topology of a design space to achieve an optimal solution. This topic has been studied by researchers for many years, but until the advent of AM, many designs could not be fabricated. Given an objective function (such as mass minimization) and a set of constraints (peak stress, displacements, etc.) the problem is evaluated over one or multiple load cases. The results of the finite element analysis are used to modify the stiffness tensor of the design space. Upon convergence of this iterative process, the results may be interpreted as relative densities. A threshold is established and elements below the threshold are removed from the design space, while all other elements are assumed to be fully dense.

Product performance may be greatly enhanced by combining AM with topology optimization techniques. Traditional design for manufacturability rules are discarded and material is optimally distributed for the specified loads and constraints. Optimization techniques may be applied to minimize mass, maximize stiffness, tune a structures natural frequency, or to minimize thermal gradients. Substantial economic benefits may result from the application of these techniques.

Available software to perform topology optimization is fairly new and contains some difficulties in the workflow. Challenging aspects of this process include: balancing conflicting constraints, checker boarding, correctly setting the cutoff threshold, and converting the resulting model into a .stl file in preparation for AM. Resulting designs are often organically shaped with truss structures commonly appearing. These designs must be evaluated to ensure manufacturability with AM.

**Mesostructure Design**

The mesostructure of a part includes design features on the scale of 1 mm – 10 mm. The geometric freedom of AM allows for control in the design of structures on this level. Uniform or conformal, lattice or random structures on this scale may be integrated into a part’s design to influence the macro properties of a component. These structures have been shown to improve the strength to weight ratio, stiffness to weight ratio, heat transfer properties, and dynamic properties. Modification of part performance through design of the mesostructure is an interest in many research institutions. This fabrication capability allows for the incorporation of auxetic or negative stiffness structures that create unique material properties that may benefit a component’s performance.

Mesostructure design is challenging because of heritage parametric CAD modeling techniques. Even relatively small components may contain thousands of individual struts or features when the mesostructure is modified. This creates large models that are difficult to manipulate, .stl files that are difficult to clean in preparation for fabrication, and difficulty in analyzing behavior with finite element analysis. Mesostructure design may be used in conjunction with topology optimization techniques. By setting two cutoff thresholds for the resulting element density distribution, three regions may be identified: elements to remove, elements to be replaced by lattice structures, and elements to become fully dense. Once these regions are identified, a second optimization routine may be applied to optimize the thickness of each strut for the given case.
Economics of Additive Manufacturing

The economics of additive manufacturing are highly influential in the adoption of this technology. Despite its technical capabilities, if an economically beneficial case cannot be created for its application, AM will not be utilized. Therefore, a detailed understanding of how the characteristics of AM affect the project economics is imperative. To address this, AM’s manufacturing paradigm will be discussed, as well as AM’s impact on product lifecycle costs and the supply chain.

Manufacturing Economics

The high cost of tooling is one of the most prohibitive factors that limit product development and manufacture. This is especially true for relatively low volume, niche, and custom products. The high cost of tooling greatly limits the product design, range of materials, and the complexity & custom-aspects of a product. Off-the-shelf solutions are frequently used that provide the necessary economies of scale but can often detract from the design intent. Even when tooling can be justified, there is often a long lead-time for their delivery that can greatly affect the time-to-market of a product and thus the competitiveness of companies. Mass-production is employed to amortize the cost of tools over a high number of parts. Additive manufacturing creates the possibility for affordable, highly complex, custom parts since there is no need for high volumes to offset the cost of tooling.

Lean Production

The lean paradigm of supply chain management encompasses the idea of reducing waste throughout the supply chain. The waste may occur as time or materials. This has resulted in the popular supply chain model Just-In-Time manufacture. The lean paradigm relies on some fundamental market principles for it to be effective & may be unsuitable for many products. These principles are primarily concerned with aspects of demand choices and demand patterns. The lean paradigm suits products that have a long product lifecycle, low margin, low product variety and accurate forecasting of demand, and generally where the market order winner is cost.

Agile Paradigm

The agility paradigm relies on using market knowledge and a virtual corporation to exploit profitable opportunities in a volatile market place. Agility focuses on lead time compression, rather than the elimination of waste. The use of flexible production methods allows fast reconfiguration of processes to cope with consumer demand. Variability of consumer demand defines the motive for agile manufacturing. Thus, it is suited to products with a short lifecycle. The market order winner for agile supply chains is not cost, but availability. The driver for the successful implementation of an agile supply chain is market information; the forecasting of demand. The information regarding a customer’s preferences drive the pull of products from the manufacturing environment, with an associated increase in cost to accommodate the inevitable increase in costs associated with changes in build methods and products.

Leagility Paradigm

Bringing together lean and agile supply chains to appropriate greater value is the concept of leagility. This paradigm aims to develop the efficiencies of a lean supply chain into an organization where it would be possible to take these cost advantages and use them to gain market share in more volatile markets normally served by agile supply chains. A leagile supply chain must be integrated effectively to produce a supply chain that can provide down-stream (towards the customer) responsiveness and up-stream stability. Traditionally, this has been achieved through postponement. Postponement delays certain activities within the supply chain until the customer order has been received. This decouples the supply chain to remove down-stream volatility of the customer demand and to act as a buffer to those process up-stream.
Additive Manufacturing Paradigm

AM allows for lean production in a responsive manner without the need for postponement. AM machines would become the decoupling point. Orders are only pulled off at the request of the customer. With this concept, there would be no stock outs, as all products could be produced to order, plus the threat of obsolescent stock would be negated as the only stock necessary to hold would be raw material and design data.

This technology shifts the cost from skilled labor operating machinery to AM machine and materials. A further driver for the reduction of costs may be in the product design. AM processes may make traditional designs obsolete. Process production may provide cost savings for certain parts and components by reducing assemblies. AM could offer the first truly agile supply chain paradigm, providing goods at low cost through the benefits of lean principles with the fast reconfigurability and response time required in volatile markets. This could lead to reductions in stock levels, logistics costs, components costs (through reduction in assembled components) and increase the flexibility of production.

Economic Benefits from Additive Manufacturing

- Batch sizes of one; elimination of tooling, jigs, and fixtures, therefore no associated amortization of tooling costs.
- Products can be brought to market more quickly, with lower cost & risk.
- Enables production of highly complex geometries that are impossible to make traditionally. Allows for optimized parts & reduction of material use.
- Design for manufacture principles no longer apply. (i.e. Design of split lines into products to enable removal from tooling, or need to maintain constant material wall thickness to eliminate shrinkage in casting.
- More functionality may be added into parts.
- The same part may be manufactured at multiple locations that are close to customers. This can mitigate single-source supply chain risk while eliminating many stages of traditional supply chains, including transportation of finished goods, thereby reducing lead times, inventory, and logistics costs.
- Little waste (especially when compared to traditional methods).

Scenarios that Benefit from Additive Manufacturing

- Low-volume production is required.
- Complex product-design geometries are prevalent.
- Fixed-cost tooling cannot easily be amortized into the piece-part price.
- Product-launch risk is high.
- Investment is problematic.
- The customer base is widely distributed.

Lifecycle Economics

Direct costs of AM are often too high in comparison to traditional manufacturing. For many cases, total costs for AM are lower when the entire lifecycle costs (LCC) are considered. This technology modifies the production process and supply chains during a part’s lifecycle, which strongly generates benefits. Business processes starting from powder production and ending with part recycling need to be considered to acquire a full view of lifecycle cost. The knowledge about these processes will help designers understand the influence of part redesign.

Most costing models published in literature are strongly focused on the pure production costs and do not convey the overall benefits of the technology. The methodology for selecting appropriate parts must include a means for estimating lifecycle costs. As AM creates benefits along the supply chain, the whole product lifecycle needs to be considered for properly assessing lifecycle costs. The “intrinsic product lifecycle” is considered, meaning, the lifetime of a product from the first idea until disposal of the part. During the lifecycle, the product creates costs. These costs occur on the side of the manufacturer as well as on the side of the customer.
Lifecycle costs consist of six major phases:

- **Conception & Definition:** In the initial phase, the costs for requirements definition and design analysis constitute the major cost structure.
- **Design & Development:** Evaluation of different aspects of the product design occur during this phase. Considered costs include technical drawings, the component design, QM planning, prototyping, testing, and the production planning.
- **Production:** During the production phase, a “Time Driven Activity Base Costing” approach is taken to consider the different influence factors on the basis of the use of resources. For the estimation of cost relevant processes, the process steps of the initial model are simplified into four main processes:
  - Preparation of the building job
  - Production of the building job
  - Manual removing of parts and support
  - Post processing to enhance material properties

These costs contain the aspects of material and machine costs considering the material-machine-combination as well as personnel costs, energy and consumption materials, post processing, and quality control. Complexity factors may be used to account for the different complexities of the building jobs. One of the major challenges is calculation of the building time as the influence of the building speed is one of the most important cost factors.
- **Installation:** The installation phase contains the costs for the transportation and installation of the product. In this phase, cost savings may be demonstrated with the use of monolithic structures to reduce assemblies.
- **Usage & Maintenance:** This phase includes the costs to utilize and maintain the part. Design improvements from AM are realized in the usage and maintenance phase. For example, reduction in mass results in a decrease in usage costs. The reduction in logistic and warehousing costs associated with the cost for storage of spare parts and tooling must be considered.
- **Disposal:** In the disposal phase, the disassembly costs and the residual value of the material or alternatively the disposal costs are included.

A LCC analysis is required to evaluate the total economic impact from fabricating a component with AM. A large amount of information and familiarity with the lifecycle of components is required to perform a valid LCC analysis. The important factors vary greatly between industries, industry segments, and individual companies. Once the most important factors are determined for a specific usage case, the model is easily adapted to similar components. During the LCC analysis, the following should be considered: component application, mass impact, cost impact, supply chain impact, obligatory certification, and obligatory quality tests.

**Impact of AM on the Supply Chain**

Indirect cost savings along the supply chain as a result of using AM are often overlooked. The cost for replacement parts includes the cost of capital, warehousing, documentation, insurance, taxes, and costs due to the excess of age of the components, approval renewal, damage or theft. Components that have been redesigned for AM may be able to be stored in a “digital inventory.” Components in this digital inventory will greatly reduce the cost mentioned above since they will be able to be produced on demand. An example of the cost saving potential along the supply chain in the context of spare part logistics is presented below.
Cost-saving potential of AM in the context of spare part logistics:

- Logistical point of view
  - Increased speed of processes
  - Higher flexibility
  - Reduced delivery cost
  - Reduction of product down time
  - Better adherence to schedule

- Designed Part
  - Design changes are facilitated
  - Elimination of tooling
  - Function improvements

- Warehouse
  - Reduction of insurance, taxes, and possibility of damage or part theft
  - Approval renewal not necessary
  - Documentation of stored parts reduced
  - Storage limits not exceeded

- Lower Inventory
  - Smaller warehouses
  - Lower capital cost
Candidate Part Selection Methodology

Additive manufacturing has great potential for improving time and cost efficiency for many products, but potential users often struggle to integrate this technology in their business. Compared to traditionally manufactured parts, AM production costs seem too high and misapplication of the technology will lead to disappointment in its performance. The systematic selection of appropriate feasible part candidates is critical for the sustainable and successful integration of this technology.

In most cases it is not sufficient to look at a part that is manufactured traditionally and simply switch to AM. Literature has shown that economic and technical results are poor when parts that were designed for traditional manufacturing are produced additively. Occasionally, limitations of the technology don’t allow manufacturing a part with AM. Better results will be obtained if all of the interfaces and functionalities are taken into account and the part is redesigned to add value with the capabilities of AM. Design rules specific to additive manufacturing must be followed when using the technology.

This highlights the fact that a selection of appropriate parts is critical for the successful and economically beneficial use of AM. Part selection should be approached in a manner to minimize the effort of the project and for requirement gathering. A collaborative effort between the part owners and experienced additive users is necessary for a successful redesign. The main goal of this methodology is to assist inexperienced users in identifying feasible part candidates for AM production.

As a large amount of economic and technical information is required to perform a component redesign for AM, assessing appropriate part candidates is time consuming. The methodology presented below consists of 3 major phases, and is designed to reduce the effort for information collection before appropriate parts are selected.

Methodology Overview

The three phases of the methodology are designed to reduce the number of part candidates with as little information as possible. This approach will minimize the effort in requirement collection. In the first phase, an opening presentation is given to inform the end-users about the capabilities and limitations of the technology. The primary goal is to shift the mindset from design for manufacturability to design for additive manufacturing. Opportunities for successful AM application will be presented to demonstrate the capabilities of the technology. The technical possibilities, technical solutions, and economic merit of successful applications of AM will be presented to help designers think about possible solutions for their company. After the initial presentation, designers will screen their parts with the known limitations of AM and will create a list of potential part candidates.

In the second phase, the list of potential part candidates will be input into a value benefit analysis to determine the most promising candidates. An assessment matrix containing weighted criteria regarding the application, economic, and technical factors that are most important will be generated with the help of managers and designers. The list of parts generated in Phase I will be rated with the assessment matrix. The top rated parts will be discussed again to determine a starting point for application.

In the final phase, the technical changes and total integration of each of the finalist parts will be discussed. Part requirements and technical information will be gathered to gain a better understanding of the part and its environment. A profile of each part will be developed to aid in understanding the full potential of a solution. Once the profile for each of the finalist parts is complete, the profiles will be compared to determine the most promising candidate for redesign. If the results of the analysis are negative for a certain candidate, the production values can be
adapted again to future forecast of the technology. This can help to define the optimal point to reconsider the use of the technology.

**Information Phase**
The candidate part selection methodology begins with the Information Phase. An opening presentation will introduce the technology to a group of program managers and designers. The primary goal of this phase is to describe the capabilities and limitations of AM to enable the participants to start the internal part screening. With the help of examples that demonstrate the advantages of the technology, the current technical applications are presented. Limitations of the technology are explained in detail along with a general discussion of the basic design rules for AM.

Following the initial workshop, the users will use the basic design rules and limitations of the technology to screen potential part candidates. After reviewing their programs, the list of potential part candidates will be generated that meet the basic limitations of the technology. More information will be gathered on these candidates, and they will be assessed in the next phase.

<table>
<thead>
<tr>
<th>Steps</th>
<th>Content</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raise Awareness for the Technology</td>
<td>Presentation of the Technology</td>
<td>Principles of AM are Understood &amp; Ability to Begin Part Screening Gained</td>
</tr>
<tr>
<td></td>
<td>Presentation of Sample Parts</td>
<td></td>
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<tr>
<td></td>
<td>Presentation of Benefits (Economic &amp; Technical)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Presentation of Limitations</td>
<td></td>
</tr>
<tr>
<td>Internal Part Screening Process</td>
<td>Distribute Material to Product Managers</td>
<td>Part Candidates Identified from Multiple Products and Product Divisions</td>
</tr>
<tr>
<td></td>
<td>Use Presented Information to Internally Screen Parts</td>
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</table>

**Assessment Phase**
During the Assessment Phase, the parts meeting the limitations of AM are further analyzed to determine which parts have high potential for economic and technical success. As different aspects are important to different industries and segments, the Assessment Phase begins with a workshop to determine the evaluation criteria that are critical to the user. This criteria is weighted and integrated into an assessment matrix. Information is gathered on the candidate parts to allow the users to fill in the matrix. The assessment matrix is used to rank the parts and identify which candidates required deeper evaluation.

<table>
<thead>
<tr>
<th>Steps</th>
<th>Content</th>
<th>Results</th>
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</thead>
<tbody>
<tr>
<td>Discussion About Possible Part Candidates</td>
<td>Define Rating Criteria in Assessment Matrix</td>
<td>Defined Rating Criteria &amp; Preliminary Scored Parts List</td>
</tr>
<tr>
<td></td>
<td>Rate Part Candidates with Preliminary Assessment Criteria</td>
<td></td>
</tr>
<tr>
<td>Information/Requirements Collection for Part Candidates</td>
<td>Define Requirements of the Part</td>
<td>Background Information Gathered on Part Candidates</td>
</tr>
<tr>
<td></td>
<td>Identify the Function of Structures</td>
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<tr>
<td></td>
<td>Determine Economic Aims</td>
<td></td>
</tr>
<tr>
<td>Expert Assessment of Selected Part Candidates</td>
<td>Estimation of Post Processing Steps</td>
<td>Well Justified Rating on Part Candidates</td>
</tr>
<tr>
<td></td>
<td>Estimation of Optimization Potential</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rate Part Candidates with Secondary Assessment Criteria</td>
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</table>
Decision Phase

During the Decision Phase, all relevant information and requirements of the top ranked part candidates are collected to determine which part represents the best candidate for AM redesign. Information Forms will be provided to assist in collecting the information and requirements necessary to make the final decision. Economic aspects of part manufacturing are included in this phase to estimate the economic benefits of redesign by evaluating the lifecycle cost. The more detailed information will enable a well justified part selection for AM redesign. Once a part is selected, a final workshop is held to determine the strategy for redesign and AM implementation.

<table>
<thead>
<tr>
<th>Steps</th>
<th>Content</th>
<th>Results</th>
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</thead>
<tbody>
<tr>
<td>Workshop on Final Part Selection</td>
<td>Define Strategic Direction</td>
<td>All Relevant Information &amp; Requirements of Top Ranked Parts is Gathered</td>
</tr>
<tr>
<td></td>
<td>Discuss Function and Redesign</td>
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<tr>
<td></td>
<td>Generate Ideas for Redesign</td>
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</tr>
<tr>
<td>Decision on Part for Redesign</td>
<td>Identify Most Promising Candidate</td>
<td>Selection of Final Part &amp; Determination of Redesign Responsibility &amp; Strategy</td>
</tr>
<tr>
<td></td>
<td>Calculate Part Costs</td>
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<tr>
<td></td>
<td>Determine Final Requirements List</td>
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This methodology allows users with only basic AM knowledge to perform internal part screening for applicable AM candidates in their own company with a reasonable effort. These part candidates can then be discussed with experienced AM users in order to find the most promising cases, which allows companies an economical use of the AM technology.

Once candidates have been selected for redesign, the black box principle is applied. This principle identifies the main functions and environments of the products targeted. This maximizes the various advantages and design freedom offered by AM. The assessment matrix and the part information forms help to ask the right questions in order to reduce the effort for requirements collection. Focusing on parts suitable for AM identified with the help of the assessment matrix also helps in saving money as no effort is spent on parts which are not suitable or not promising for the use of additive manufacturing.

Key aspects for cost efficient AM production:

- Selection of an appropriate part is crucial
- Selection of an appropriate process and material
- Black box design: Don’t use existing parts
- Use proper design rules
- Keep utilization rate in build chamber high
- Consider product lifecycle
- Don’t over optimize parts

Assessment Matrix

During the Assessment Phase, an organized approach to screen candidate parts is necessary to determine those with the highest potential. In the top section of the matrix, the individual parts for consideration are described. Typical information includes: Brief description of the function, typical production quantities, production costs, dimensions, the mass of the part, and the currently used material. An initial estimation of how many parts can be placed on the AM building platform is calculated based on the bounding box dimensions of the part. The description is completed with a picture of the part candidate. This basic information is used for part assessment and a rough economic analysis later on.
Criteria, definitions, and ratings are defined according to different industries or the different strategies of the user. Every section is structured into different main categories that include several sub criteria. These sub criteria can be rated in a manner similar to a value benefit analysis. The matrix may be adapted to several different applications through a change of ratings or adaption of sub categories.

**Preliminary Assessment Categories**

**Size Limitations:**
This size of the build chamber significantly limits the different fields of application. EBM Q20 build chamber is 350 mm (13.78”) in diameter by 380 mm (14.96”) high.

**Part Classification:**
This category defines the part in regards to complexity and consist of two sub criteria. First, the complexity of the manufacturing of the considered part is evaluated. Complexity of the part is mainly defined on how complex the part is to manufacture traditionally. Parts with high buy to fly ratio are usually very complex to manufacture. Highly complex parts are normally better candidates for AM. Secondly, the availability of similar parts in a company must be rated. Is this part a typical problem in a company? Redesigning a part for AM which might be slightly adapted and used for other products will be more economical and beneficial for a company.

**Reduction of Assemblies:**
One of the main advantages of AM is the possibility of functional integration into single piece assemblies. This category is subdivided into criteria for the specifications of the number of external interfaces, the options of reduction of assemblies, and the merge of part functions. If parts are assembled to other adjacent parts due to milling constraints, a suppression of assemblies is possible and achievable with AM. Many interfaces may lead to functional integration or an integral design. Integral design will create benefits due to the significant reduction of required parts and a reduction of assembly time. AM could enable the functional integration such as integrated heat insulation, high flexibility, or integrated joins.

**Necessary Post Processing for AM Part:**
As discussed in the limitations section, AM technology can only achieve certain surface qualities and often need post processing for different reasons. This is a disadvantage of the technology and some heat treatments or surface finishing steps may be required. This category is subdivided in the part applicability for post processing and determines the amount of functional surfaces. Build orientation of the part must be considered as there might be an additional need for post processing if many support structures are used.

**Applicability of Already Used AM Material of Parts:**
This category helps to find appropriate material. Not all information is available for all materials. The sub-criteria in this section asks for current materials and the possibility of a material change. Furthermore, the materials environment and the different load cases are considered here in order to be able to identify possible materials for a redesign if a material change seems to be necessary or beneficiary.

**Compliment of Specific Geometric Conditions for AM:**
This category aims on making sure that the part candidates can be manufactured with AM technology. The use of Design Rules is important to achieve the desired results. Current design aspects must be considered when determining applicability of AM. For example, large solid block structures may be problematic due to the risk of residual stresses. These aspects could be overcome with the integration of lattice structures.

**Property Improvement of Part by Design Optimization:**
This category aims to identify the optimization potential of a part by the use of enhanced design possibilities by AM. A consistent set of ratings and definitions are applied and analyzed in order to achieve repeatable results and to help the end users quantify the potential benefits.
As Built Material Consumption:
AM can significantly help to reduce scrap as the only wasted material is the extra stock and material of support structures. With intelligent product design even these can be minimized. Therefore the as built material consumption criteria is the difference of the part edge volume (outer dimensions/bounding box) and the actual part volume. This is similar to the term buy to fly ratio, which is frequently used in the aerospace sector.

Current Processing Time:
The processing time criterion aims on estimating processing times regarding the traditional manufacturing. Long traditional manufacturing times are favorable for the use of the AM technology. The second criterion evaluates the part’s impact on the entire product development process. Reduced lead time is valuable for parts which must be completed before the design of upstream components.

The rankings of the preliminary assessment categories are designed to be mainly filled in by non AM experts. These criterion will be scored and the top ranked parts will be evaluated by experienced AM users. From here the total list will be narrowed down to a maximum of 3 different part candidates. Only these candidates will be regarded in the secondary assessment categories in the matrix. Selecting these three part candidates will be the end of the assessment phase. Experienced AM users will mainly perform the secondary assessment.

Secondary Assessment Categories

Material Change:
In this category, the part is rated regarding the possibilities to produce the part with the adapted AM material and meet the required strength/stiffness of the part. Furthermore, an estimation of necessary post processing steps will be rated. This will include necessary special treatments due to material change to fulfill environmental requirements (i.e. corrosion, stress corrosion cracking, outgassing, etc.)

AM Material Consumption:
The raw material required for production with AM needs to be calculated. This material includes part volume, material for supports, extra stock (to be finished off), and non-recyclable material. Buy to fly ratios should be compared along with raw material costs for each process to determine economic benefits.

AM Processing Time
The total time for fabrication and post processing with the AM process will be estimated. This includes the lead, process, and post processing time. For AM, the process time needs to be scaled down to one piece. These values will then be compared and result in scores for the parts.

Economic Aspects:
Here the parts costs for AM and post processing are compared to traditional costs. This results in the calculation of a cost ratio.

After the finalization of the secondary assessment, a rating for the last three part candidates will appear. Special information collection sheets for part requirements have to be filled out by the part owner. This will help the experienced AM users in a final part assessment. The final decision for a part redesign will be taken in a last discussion with the AM experts and the part owners before the redesign process begins.