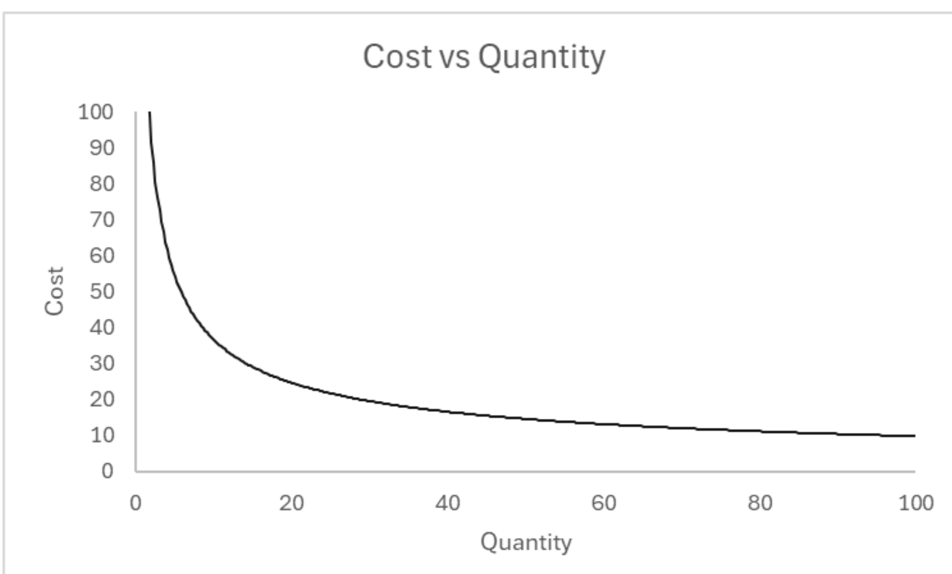
Part 1

"Economies of scale" is a common concept. It represents the idea that as operations are conducted on increasingly larger scales, the costs of performing the operations become increasingly smaller on a relative basis. Conventional manufacturing methods used to create modern products or parts have a nature such that they can benefit from economies of scale. The reason for this is that the costs of capital to produce a part can be amortized across the parts it produces, and if it produces more parts then each part bears a smaller portion of the costs. Simply put, if I spend $100 purchasing a machine to make parts, and only make 10 parts to sell, the amortization is $10 per part. Alternatively, if I make 100 parts to sell then the amortization is $1 per part.

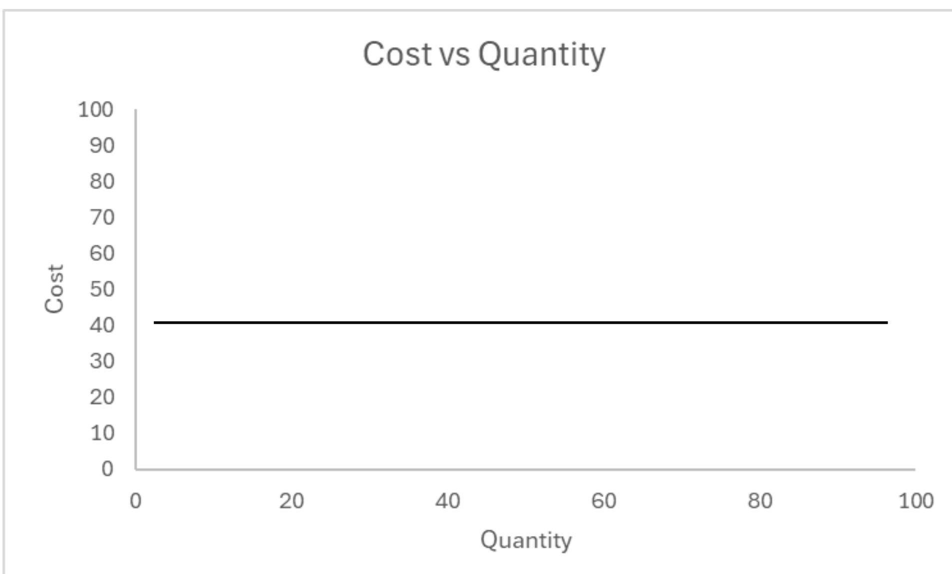
Eventually, however, the quantity being produced approaches a limit where costs no longer decrease because there is a minimum cost of making the parts which can be a factor of material costs, energy costs, engineering costs, etc. and also minimum acceptable profit margin. In other words, it doesn't matter how many aluminum brackets I want to make, if each bracket costs $1 in aluminum feedstock, then the minimum material costs are $1.

So, economies of scale can be modelled on a cost versus quantity graph. The fancy technical way to describe the behavior is that the trend is a downward sloping, concave upward line which approaches an asymptotic limit representing the minimum possible costs of production. The less pretentious way to say it is that it is a steep line that becomes flat.

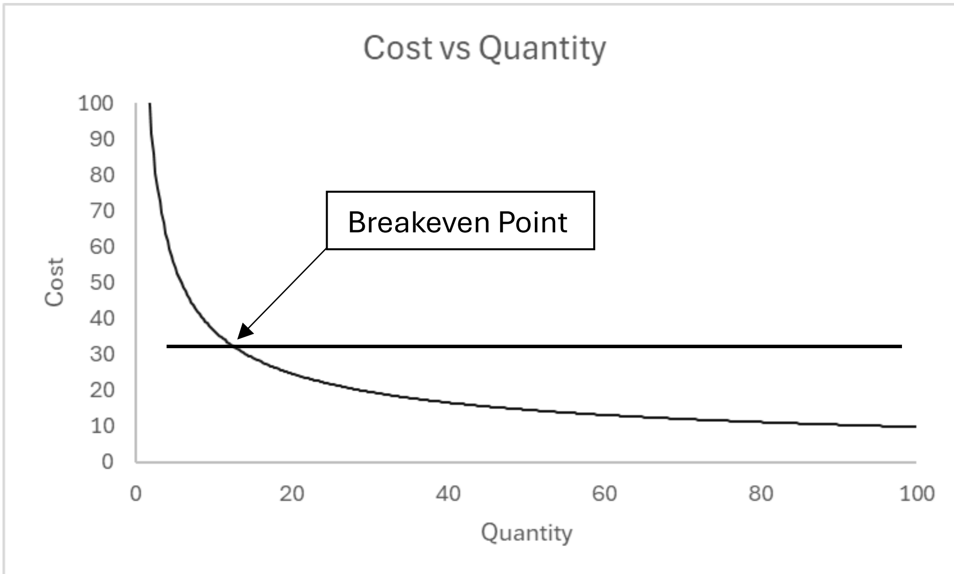


Additive manufacturing does not benefit from economies of scale. This is because the inputs for every single part being made are exactly the same, no matter how many are produced. To factor in the capital costs for making a part, one needs to determine the depreciation rate of the additive manufacturing machine being used which is calculated by the cost of the machine divided by the expected lifespan of the machine. This figure can be calculated in $/year. Convert this into $/hour by determining the expected operational hours of the machine. With this hourly rate for the additive manufacturing machine, one can then apply the hourly rate of the machine to the number of hours it took to make the part. Also consider the running electricity costs, etc. in the hourly rate.

One can see that in the calculation for the cost of an additively manufactured part, quantity played no role, therefore it does not affect cost. Of course, it could be pointed out that if multiple parts are made in a single run, then the hourly rate can be divided by the quantity of parts being made in that run. Although it is true that this does reduce costs per part, it is performed on a very local basis with very fast-approaching limitations on quantity, generally not yielding an economy of scale effect. The assumption should be made that when making parts with additive manufacturing, the highest quantity of parts being made in a run is occurring, in which case the cost curve is flat.



So, the cost curve for conventional manufacturing technologies is a downward sloping line which hits an eventual limit on cost per part, and the cost curve for additive manufacturing is a flat line wherein the costs of making a part are not changed by the quantity produced. The relationship between the two curves yields more information.



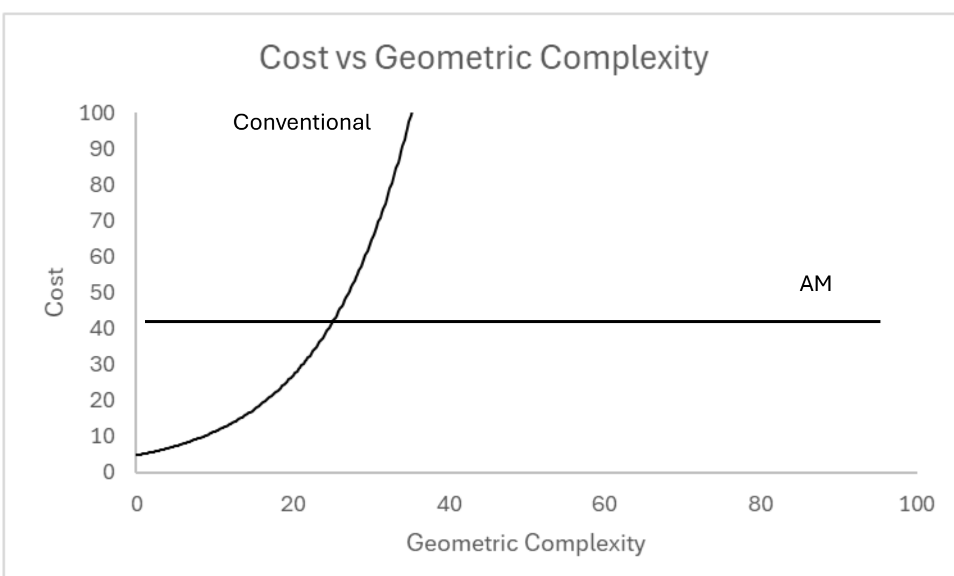
When overlaying the trends, one notices an intersection of the curves. At the lower end of the quantity spectrum, the additive manufacturing curve offers a lower cost of production per part, whereas on the higher end of the quantity spectrum the conventional manufacturing curve offers a lower cost of production per part. The intersection point is called the "breakeven point" and represents the quantity wherein it is cheaper to use additive manufacturing for quantities less than the breakeven point, and cheaper to use conventional manufacturing for quantities greater than the breakeven point.

This observation makes it clear why additive manufacturing has been associated with rapid prototyping. As it is a convenient and cheap method of manufacturing small quantities of parts but as the quantities increase, it quickly becomes uneconomical. The conclusion to be drawn from this is that the operating range for additive manufacturing is everything to the left of the breakeven point, and the operating range for conventional manufacturing is everything to the right of the breakeven point.

Part 2

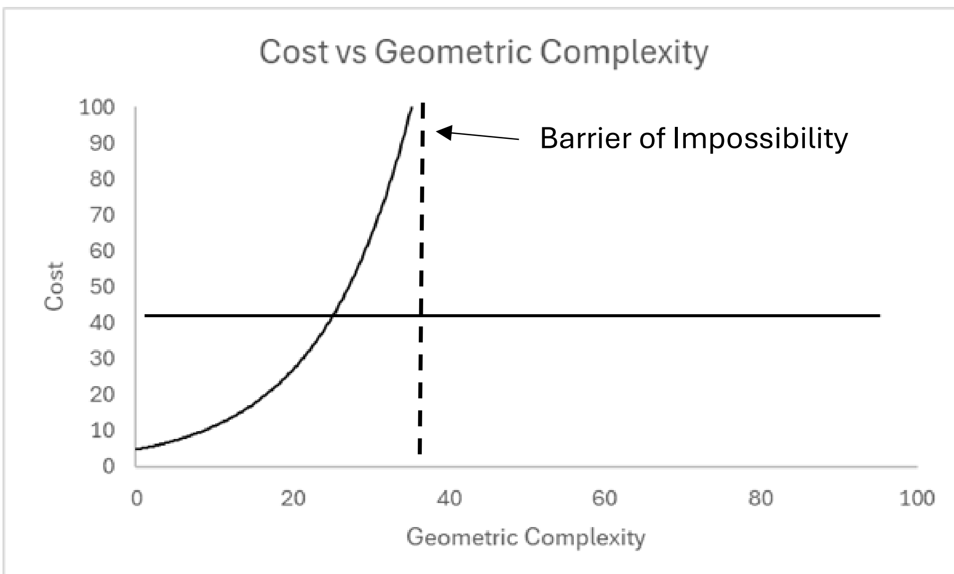
The story of competition between additive manufacturing and conventional manufacturing methods cannot be told through one graph, but rather it should at least be told through two graphs. The second relationship that will be analyzed is the relationship between cost versus geometric complexity of the part being produced. Cost is already understood as the dollars it takes to make a part. Geometric complexity is literally how complex the shape of a part is. This could be thought of on the spectrum starting at a geometrically simple object, such as a square box, all the way up to a geometrically complex part, such as an all-in-one rocket engine.

In almost all cases, the geometric complexity of a part does not impact its cost of manufacturing if it is being additively produced. This is because the nature of additive manufacturing, that is, adding material to create a part layer by layer, allows for the entire geometry of the part (both external and internal) to be exposed at some point during the build process which allows for extreme flexibility in how the part is ultimately shaped. This yields external and internal geometric control. Conversely, with conventional manufacturing methods, only the external features of a part are able to be manipulated and controlled. This means that there are certain geometries which are outright impossible to make with conventional manufacturing methods such as casting, forging, or cutting. To overcome this impossibility barrier, parts might have to be assembled from multiple components or go through multiple manufacturing processes which both increase costs but do not guarantee the ability to create any geometry. This reality is similarly modelled in a graph.



Observing the graph, one notices there is a breakeven point. This represents the point at which a part's geometric complexity contributes to its costs such that any more complexity would mean that additive manufacturing would become the more economical manufacturing method, as the conventional processes witness steep increases in cost. This increase in cost is a factor of tooling becoming more expensive and complex to produce and more processes and time needed to make the geometry.

An interesting phenomenon to note is that the conventional manufacturing curve approaches a vertical asymptotic limit, meaning that it has limits in the geometric complexity that it can produce. Going any further to the right would mean that the proposed geometric complexity would be impossible for the conventional manufacturing methods to produce.

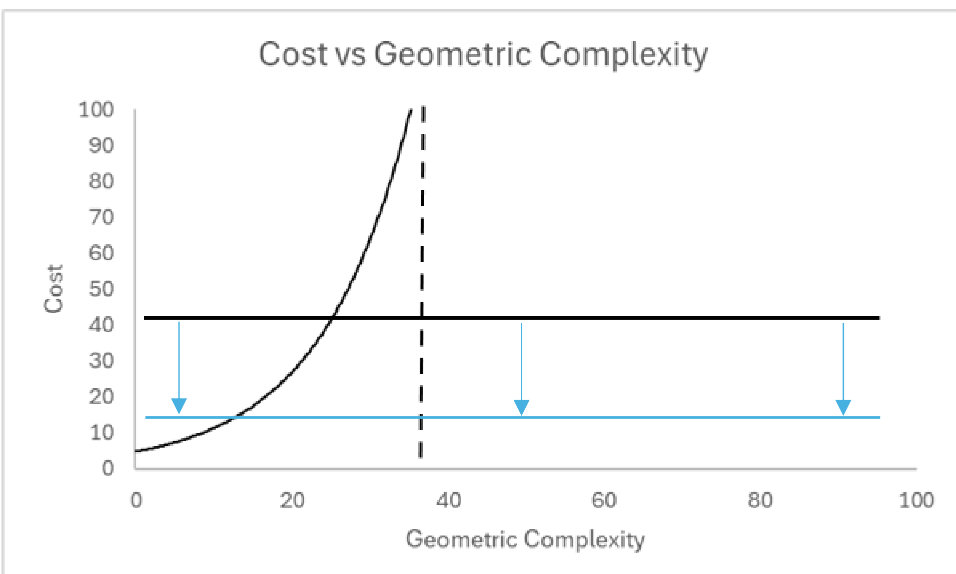


The dashed line in the graph represents the "barrier of geometric impossibility". This line is the limit of what conventional manufacturing methods can feasibly produce. Such geometries are triply periodic minimal surfaces like internal lattice structures or gyroids, topology optimization, and internalized fluid flow paths. All of these geometries are incredibly difficult and costly (if not outright impossible) to produce with conventional manufacturing methods. However, these same geometries are extremely easy for additive manufacturing to make. Also, the intersection of the additive manufacturing curve and the conventional manufacturing curve similarly represents a breakeven point along the lines of geometric complexity.

Part 3

The graphs above outline the competitive landscape between additive manufacturing and conventional manufacturing. Simple analysis indicates where each technology is most competitive, being that additive manufacturing is competitive along the lines of low quantity, high geometric complexity production whereas conventional manufacturing is competitive along the lines of high quantity, low geometric complexity. An important feature of this landscape to note is that conventional manufacturing technologies do hit a geometric limit, where they are totally unable to compete at all, leaving the field completely open to additive manufacturing. This presents an opportunity for additive manufacturing to redesign and sell products that have typically been produced with conventional manufacturing technologies assuming the performance gains are marketable.

I believe that products should be optimized for their application, not for their manufacturing feasibility. If products are made with conventional manufacturing processes, that means they are to the left of the geometric barrier, but if they stand to gain performance improvements by moving to the right of that barrier, then they inevitably need to be made with additive manufacturing. If the cost curve of additive manufacturing is pushed downward, then it can become more competitive with conventional manufacturing on scale.



Is additive manufacturing trying to compete with L-brackets for shelves? No, it should compete with things like heat exchangers for data center chips, battery packs, or home air conditioning units. It should compete on lightweighting components for aerospace, drones, or cars. Additive manufacturing should focus on products where performance gains matter a lot to the end user, where performance gains can be realized with complex geometries like lattices, gyroids, and internal fluid flow paths.

I have an expectation that with computational engineering abilities becoming more common place through advancements in machine learning and AI, we will shift away from designing parts through CAD programs in which the design of a part is limited to what a person can conceive of and draw. I also think that lowering the cost curve of additive manufacturing and the demand for increased geometric complexity will become something of a positive feedback loop. If some parts need to be more complex, then there will be a demand for additive manufacturing, and if additive manufacturing can become more cost effective, then more parts can become better optimized for their applications through increased geometric complexity. This feedback loop will quickly find high volume product areas.

Finally, one might suggest that "complexity" for complexities sake is a mortal sin in design and engineering. The counter argument is that the manufacturing of these geometrically complex shapes isn't any more difficult as the manufacturing of a simple shape if additive manufacturing is used. Furthermore, if increased geometric complexity leads to performance gains, then it's a good thing.