Additive Manufacturing – A Future Revolution in Supply Chain Sustainability and Disaster Management

Krishnamoorthi Muthukumarasamy, Pratheep Balasubramanian, Aniket Marathe and Mohamed Awwad
Industrial and Systems Engineering Department
University at Buffalo, The State University of New York
Buffalo, NY 14260, USA
km325@buffalo.edu, pratheep@buffalo.edu, marathe2@buffalo.edu, maawwad@buffalo.edu

Abstract
The supply chain sustainability and disaster management are the fields having perennial scope for improvements. Despite various technological advancements, the conventional method of supply chain system remains highly inadequate in response to countering natural disasters and maintaining sustainability. This is where the idea of additive manufacturing (AM), a rapidly growing technique, can be incorporated to ensure a robust and resilient supply chain network. This paper focuses on evaluating the existing systems through relevant case studies and hence providing supplemental methodologies based on additive manufacturing and optimized purchasing strategies. In addition, utilization of such techniques in inventory management of parts and products and warehouse design & construction are also covered. Moreover, the scope of this potential breakthrough is wide enough in such a way that it can be amalgamated with the supply chain networks of all kinds of industries. In addition to all these functional improvements, this innovation would also bolster the concept of green and lean supply chain networks thereby contributing to an eco-friendly environment.

Keywords
Additive Manufacturing, Supply Chain Disruption, Supply Chain Sustainability, Distributed Production.

1. Introduction
Additive manufacturing is technology that creates a physical object using three dimensional (3D) designs. The 3D models would be sliced into two dimensional (2D) layers and then be printed layer by layer in the 3D space. Over the years, leading industries have focused on developing their supply chain networks to achieve fullest extent of customer satisfaction. Several technological advancements have paved way in doing so, but additive manufacturing could profoundly revolutionize the prospects of future supply chain networks.

In a traditional methodology, manufacturers work along with their neighboring supply chain echelons to produce the product and move it through the chain which ids then delivered to the customers. Incorporation of additive manufacturing in the supply chain would potentially reduce the number of echelons in the entire supply chain leading to a reduced lead time which is the main key to achieve customer excellence.

Another major challenge faced by manufactures is associated with the amount of inventory that has to be held so as to cater to the needs of the customers without falling short of the demand. With the growing importance and the need for Just in time (JIT) manufacturing, the AM technology could qualify as the most suitable technology that can support manufacturers on this regard and in eliminating the storage of excess amount of inventory at any given instant.

Furthermore, recent researches focus on how AM incorporates flexibility in the supply chain specially to meet and manage disruptions and disasters. "As global businesses are growing rapidly while supply chains are becoming more complex, it is crucial for our customers to detect future obstacles along the supply chain and take early actions to mitigate business risks"(DHL, 2017). AM would be the one among the solutions to achieve this goal.
2. Hybrid AM Manufacturing

Additive manufacturing can be employed to manufacture parts with variety of raw materials such as plastics, polymers, steel, titanium, aluminum, etc. If metals are taken into consideration the major AM production methods include powder bed fusion, binder jetting, directed energy deposition, and sheet lamination. Among these methods the most widely used method for AM metal production is powder bed fusion method. In this particular AM technology, powder is spread on a build plate, in layers. The major concept of this methodology is that, the three dimensional data of the final product is extracted from a part model file. A concentrated energy source in the form of a laser or an electron beam is used to selectively melt the powder present in the build plate. This process is repeated till the point where the final product is produced. To obtain the desired final part dimensions, finish and properties, all metal AM methods require certain means of post-processing. The post-processing techniques include traditional manufacturing operations such as machining, polishing, grinding etc. Hence there is a need to incorporate the AM process with the traditional manufacturing so that the AM technology can be employed in the real-time products and applications.

It is very well-known fact that meeting the customer requirements for spare parts and obsolete parts is an inevitable challenge that every industry faces in the market. Manufacturers who can meet the customer demand on time, with the desired quantity and quality can gain the advantage over the less agile competitors in capturing the market which is the main objective of any supply chain.

In the current scenario with the traditional manufacturing it is difficult for any firm to meet the customer demand for spare parts on time due to its low volume, huge demand uncertainty and short lead times. In these situations, it is profitable for any company to make the product on its own through AM technology instead of buying parts from different suppliers as it would drastically reduce the stages in supply chain. Since most of the additively-manufactured products require post processing, the Hybrid AM process comes in handy to resolve this concern.

Making Additive Manufacturing facilities at every industry seems impractical due to the huge fixed cost and operating cost. Lower utilization rates of these machines will also lead to the negative cost impact as hybrid AM manufacturing is more suitable only for low volume and customized products. Hence locating AM hubs that can serve the need of several traditional manufacturers will be an excellent solution that can cater the requirements of meeting the customer demand on time while minimizing the overall supply chain cost. As exhibited in Figure 1 locating the optimum number of AM hubs is very crucial because if installed AM hubs are lesser than the requirement then meeting the customer demand will be difficult and on the other hand if the AM hubs are installed more than the optimum then it will lead to negative cost impact due to lower utilization rates and depreciation costs. This shows that locating optimum number of AM hubs in the suitable locations and proper allocation/assignment of the existing traditional manufacturers to AM hubs plays a critical role in making the hybrid AM process feasible for the real-time operations (Strong, Kay, Conner, Wakefield, & Manogharan, 2018).

![Figure 1. Location and Allocation of AM hubs](image-url)
2.1. Operation of Hybrid AM manufacturing process

Traditional manufacturers will receive the customer demand of the products and the digital model of the products are sent to the nearest AM hub where the products are made using the Additive Manufacturing technology. Once the products are manufactured, they are shipped to the traditional manufacturers for post processing process (Hybrid AM process). After the post processing, the products are delivered to the end customers (Danielle Stronga, 2018).

2.2. Location and Allocation of AM Hubs

Location decisions can be made using either qualitative or quantitative methods. The decision variables used in the qualitative methods are Raw material availability, labor, demand areas, transportation decisions, government policies and reach to the customers. In this work, we focus mainly on the quantitative methods for location and allocation of the AM hubs. p-Median and Uncapacitated Fixed Charge Location (UFL) methods can be used for this purpose. p-Median method can be employed if the main objective is to assign AM facilities to the traditional manufacturers to minimize the transportation distance alone. Moreover, in p-Median problem existing facility can be assigned to only one new facility (AM hub) that is each non-median is assigned to the closest median. However, in case of practical scenario various factors should be taken into consideration for location and allocation. The factors such as demand, location, fixed cost, production cost, human resource availability should also be considered for more efficient allocation. Moreover, the overall cost should be reduced and not only the transportation distance. Hence the required data - region in the US, state, number of machine shops, annual sales volume and number of employees per county can be obtained from the North American Industry Classification System (NAICS) data set.

In UFL problem the main objective is to minimize the total cost, which is the sum of location and allocation costs. Location cost is fixed cost associated with the establishing Additive Manufacturing facility. Cost of allocation will be the total logistic cost of UFL.

In addition to the implementation of Hybrid AM technology for spare parts support it can be used for manufacturing the various distinct low volume products. This statement is very well supported by the results of the survey that 82% of metal manufacturers in the U.S estimate that 50% of their products are low volume production. Hybrid AM process can be employed for manufacturing these low volume products that can lead to an increased supply chain efficiency by reducing the production lead time and meeting the customer demand on time (Danielle Stronga, 2018).

3. Vulnerability to Supply Disruptions

Majority of organizations have a false belief that they have a highly resilient supply chain. But the truth is that, they have rarely been tested with the natural disasters and hence are devoid of the preventive measures. In addition to this, a research conducted by DHL, concluded that 93% of the world’s top companies are not prepared to face the disruption due to natural disasters (DHL, 2014).

![Diagram](image)

Figure 2. Process flow in the traditional manufacturing

Natural disasters on any given day, are difficult to anticipate and the resulting impacts cannot be realized in the immediate future as well. By 2030, it is estimated that annual global economic impact of natural disasters could be up to 328 billion Euros and the World Economic Forum has suggested that significant disruption to the supply chain is likely to impact a company’s share price by 7% on average (Benton, 2016). Additive Manufacturing can play a crucial role in making the supply chain more resilient and less vulnerable to natural hazards. Moreover, it helps in reducing the recovery time of the supply chain to a significant level. In the conventional manufacturing process as shown above in Figure 2, the final product is obtained from the several levels of supply chain. The child parts (the constituents of a product) are made at different geographical locations and inventories of all these parts are maintained at their
respective locations. These child parts are then transported to the main plant where the assembly occurs. This clearly shows how vulnerable is the supply chain to supply disruption. Even if any one of the areas is affected then whole of the supply chain operations will come to a halt.

![Figure 3. Additive manufacturing process](image)

The use of additive manufacturing technology as shown in Figure 3 enables the manufacturing of products near the customer’s geographical location thereby reducing the response time, which in turn helps in achieving the maximum customer satisfaction.

4. Cost Analysis
Additive manufacturing plays a significant role incorporating Lean manufacturing principles in the production and supply chain to reduce wastes (those which does not add value to the customer).

Reduction in the inventory: Additive manufacturing helps in reducing the need of stocking large inventories of items (Especially in case of low volume, high complex items) to a great extent, thereby increasing the cash flow of the industry, which elevates the ROI.

Transportation: Since the production can be carried out near the customer’s geographical location significant decrease in the transportation cost is achieved.

Over-processing: Since the CAD modeling is directly transformed into the end, product there will be a major reduction when it comes to post processing.

Reducing the need for supply chain management: The supply chain includes purchasing, operations, distribution, and above all, integration. Purchasing involves sourcing product suppliers. Operations predominantly involve demand planning, forecasting, and inventory. Distribution involves the movement of materials and products and integration involves creating an efficient supply chain overall. Reducing the need for these activities can result in a reduction in costs. Additive manufacturing has the potential to significantly impact the manufacturing supply chain, reducing the need for supply chain management and the corresponding stages. This technology has the potential to bring manufacturers closer to consumers, reducing the number of links in the supply chain. Thus, it can help in considerable cost reduction in supply chain management aspects.

Raw Material and Machine Cost in AM: As discussed in the preceding sections, metal and plastic are the primary materials used for this technology. Currently, the cost of material for additive manufacturing can be quite high when compared to traditional manufacturing. The material costs for a selected metal part made from aluminum alloys was found to be €2.59 per part for traditional manufacturing and €25.81 per part for additive manufacturing using selective laser sintering; thus, the additive manufacturing material was nearly ten times more expensive. Increasing adoption of additive manufacturing may lead to a reduction in raw material cost mostly through economies of scale in which case it is highly beneficial. The reduced cost in raw material might then propagate further adoption of additive
manufacturing. There may also be increasing benefits out of economies of scale in raw material costs if particular materials become more common rather than an excessive abundance of different classes of materials (Gilbert, 2014).

The consolidated cost of the production and supply chain in case of incorporating the additive manufacturing varies with certain important factors including building rate, machine utilization, material cost and machine investment. It has to be noted that in each case, the machine cost (62.9% on average) contributes to major proportion of the total cost followed by the material cost (18% on average) (Gilbert, 2014).

It also has to be noted that different techniques can be adapted while printing a product through the AM technology, with stereolithography, fused deposition modeling and selective laser sintering being the most preferred. A lever was chosen to be printed out of a polymer and for experimental study and it was found that selective laser sintering stood atop compared to other methods especially in terms of machine cost metrics. It is quite clear laser sintering method is best suited for manufacturing that particular product. In terms of both product level cost, and total cost, proportion of the machine cost happens to be considerably low in case of selective laser sintering (Gilbert, 2014). Hence extensive analysis has to be performed on the selection of the AM method for different variety of products.

3.1 Cost Comparison Between Injection Molding and Additive Manufacturing

For carrying out a detailed analysis, a quantity based analysis was carried out between Injection molding (IM) and Additive manufacturing in manufacturing a lamp holder. The cost per model assembly was calculated for different product quantities including 5000, 20000, 100000 and 500000 in case of IM and the results were graphed.

Similarly, the cost per model assembly for AM P730 (EOS SLS P730 variant) and AM P390 (EOS SLS P390 variant) was calculated and the results were graphed (Gilbert, 2014)

It was clearly inferred that additive manufacturing techniques is the cost-effective method for lower production volumes are lower and that the traditional injection molding method can be employed if the production volume to be achieved is very large. In such cases, a simple break-even analysis can be performed in order to select the method of production for that particular component.

The break-even analysis would comprise of a simple mathematical model, in which the number of parts (quantity) and the cost per part are graphed against each other. The point at which the two cost curves (corresponding to IM and AM) intersect each other, is the break-even point.

4. Sustainability

Sustainability is the other important challenge faced by the traditional supply chain network. In the existing manufacturing system, the majority of the processes are subtractive manufacturing processes leading to the huge wastages of the raw materials. Whereas in the case of additive manufacturing the raw material required for manufacturing the output product is alone used and moreover 95 to 98% of the recycling can be achieved and this process is termed as the closing the loop. Hence additive manufacturing plays a huge in reducing the carbon foot print and helps in reducing the global warming. There are many real-time projects implemented by various organizations that enhances the sustainability using the AM manufacturing techniques. Siemens power generation services acquired direct metal laser sintering (DMLS) AM systems from EOS and making the shift towards make to order product manufacturing for spare parts. General Electric is manufacturing nineteen additively manufactured fuel nozzles that is five times stronger than the conventionally manufactured, improved combustion efficiency and 25% reduction in the weight. Bewell watches are the manufacturers of the customized wood watches. Wood flour and dust is a typical by products from timber and wood processing. They are using these byproducts combined with the binding agent to create a wood filament for AM process. Ekocycle cube home 3D printer uses recycled polyethylene terephthalate (rPET) in its cartridges. These cartridges currently use 25% recycled PET content and are available in red, white, black and natural colours. Kazzata is a digital repository that provides a selection of 3D CAD files of replacement parts that users can download and manufacture. Caterpillar remanufactured engines and parts and attained the same quality of new Ones. Today, 40% of the components in a reman engine are new and could be further reduced to 25% (Simon Ford, 2016). These are only very few illustrations of the real-time sustainability projects are carried out using the AM technology.
5. Real Time Case Studies

5.1. FigurePrints
FigurePrints have obtained the contract for fabricating real-time action figures of characters based on the very famous World of Warcraft game owned by Blizzard entertainment. They basically wanted to satisfy the craze for real time action figures that was at peak during the reign of this game. In order to achieve product demand and the need for variety, FigurePrints partnered up with FabZat which offers world class 3D printing services. This allowed FigurePrints to provide 3D printed, personalized statues/action figures in which variety of new designs and the name of the customers can be printed. This further played an important role in reducing the major costs associated with their supply chain network.

With the AM technology at their disposal, FigurePrints were able to offer greater levels of service especially in terms of customization and faster delivery, thereby elevating the overall performance of their supply chain (Koslow, 2015).

5.2. Mercedes Benz/Daimler
Mercedes Benz/Daimler has integrated their spare part production with AM technology which has served as a part of their “Customer Services & Parts 3D Print” line of projects. The company describes the primary aim of this series of projects as to make available the existing and obsolete spare parts for their Mercedes trucks and Daimler buses.

The major advantage of this methodology adapted by Daimler was the ability for customization and to considerably reduce the lead time which is one among the most primary goals of a supply chain in order to achieve customer excellence.

The specialty parts and spare parts are mostly made out of high-grade plastic components. Covers, spring caps, air ducts, brackets and mountings are very good examples of 3D printed spare parts adapted by Daimler. It also has to be noted that the quantity of production is maintained nominal so as to achieve the benefits of AM. In case of Daimler, selective laser sintering was the method deployed as a part of their project plan to realize the cost-effectiveness of AM technology. The plan according to them, would also help them to build the rigid system that would help them survive disruptions in case of unexpected natural disasters.

This adaptation was first infused by Mercedes Benz/Daimler back in 2016 (Daimler).

6. Conclusion and Suggestions for Future Research
This review paper has put forth the concepts and the advantages of the hybrid AM processes over the traditional process. Profound analysis on how the AM hubs can be located for minimizing the total cost of production and allocation has been carried out. Cost Benefits of AM process over traditional manufacturing have been studied from various literatures and results are explained. The AM technique has been widely adopted by various industries in real time operations for improving the sustainability and the major illustrations are stated. Assimilation of the AM technology has certain shortcomings as well, which paves way for the scope for further research that has to be carried out in order to improve the overall effectiveness in utilizing this technique to revolutionize the supply chain. Some of the areas of future research that are of primary focus are listed below.

Stair Stepping effect: Even though it is claimed that additive manufacturing helps in attaining the accuracy of the product there is the huge research going in the field of additive manufacturing in order to reduce the stair stepping effect that was shown in the above figure.

Toxicity of AM materials: It is found that raw materials that are used for AM method are not necessarily greener than materials used in traditional manufacturing (Exception- Polylactic Acid). Full environmental performance (Start to end) must be considered for evaluation not just the AM process (Simon Ford, 2016).

Energy consumption for raw material preparation: Significant amount of energy is expended during the process of refining and processing the metal ores. Hence intensive research work has to be carried out to find energy efficient methods for raw material extraction. UK-based firm Metalisys, has commercialized a process for producing titanium powder directly from titanium ore. This process requires significantly less energy to produce the titanium powder than the established Kroll process. Furthermore, the process uses a non-toxic reactant, calcium chloride, during refinement and any leftover CaCl can be reused (Simon Ford, 2016).
Thus AM technology has definitely bolstered the functioning of supply chains. While researches are still underway, modifications have to be made to overcome certain voids present in the AM technology, which would be the key to completely integrating this particular technology with supply chains. Upon doing this, industries would reach the extent of being at most successful in achieving the fullest extent of customer excellence which, by far is the ultimate goal of any supply chain.

References

Biographies

Krishnamoorthi Muthukumarasamy is a graduate student in Industrial and systems Engineering at University at Buffalo. With a Bachelor’s in automobile engineering he has a work experience of three years in Mando Automotive India Pvt Ltd as senior engineer of strategic sourcing and purchasing. He successfully presented as a research paper titled Control of Braking force under Loaded and Empty conditions on Two-Wheeler in International conference on Aerospace, Mechanical, Automotive and Materials Engineering organized by World Academy of Science Engineering and Technology held at Singapore. He excelled in applying his skills and abilities, while serving the task force team for Global Enterprise Resource Planning (ORACLE G-ERP) implementation in Purchase and Inventory management modules at Mando.

Pratheep Balasubramanian is a graduate student in Industrial and Systems Engineering at University at Buffalo. He did his Bachelor’s in Mechanical Engineering. He has done projects related to manufacturing and automobile engineering. He has a project related to developing an integrated system for automobiles in order to inflate the tires, to his name. Furthermore, he has interned at Sri Kaliswari Metal powders in the continuous improvement and manufacturing domain. In addition, he has done a project related to optimization of titanium machining. He has also done a six sigma based project at PineHill Fresh foods, focusing on utilizing the DMAIC methodology to reduce the inventory holding cost and to present an optimized logistic routing.

Mohamed Awwad is a Teaching Assistant Professor in the Department of Industrial and Systems Engineering at the University at Buffalo, The State University of New York, Buffalo, NY, USA. He received his Ph.D. and M.S. degrees in Industrial Engineering from the University of Central Florida, Orlando, FL, USA. Additionally, he holds M.S. and B.S. degrees in Mechanical Engineering from Cairo University, Egypt. Before his tenure with the University at Buffalo, Dr. Awwad held several teaching and research positions at the University of Missouri, Florida Polytechnic University, and the University of Central Florida. His research interests include applying operations research methods in the fields of logistics & supply chain, distribution center design, unconventional logistics systems design, healthcare and the military. He is a member of IISE, INFORMS and ASME.

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