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Integrating Additive Manufacturing into the Supply Chain in a Fuzzy Environment

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ABSTRACT

Additive manufacturing (AM), 3D printing, rapid prototyping, rapid development, rapid technologies and many other similar names are terms used interchangeably for rapidly growing technologies based on adding materials, layer by layer, to build the final product, in comparison to the subtractive - conventional productions. Meanwhile, the supply chain has been greatly influenced by this phenomenon. Thus, it is necessary to provide a holistic approach to the analysis and design of the system. In this paper, a supply chain model for the integration of conventional and AM facilities in a fuzzy environment is developed. This model is focused on situations where the possibility of adding new AM facilities within the traditional plants in a broader supply chain is on question. In addition, the best production levels and transportation of the chain, along with purchasing decisions and other tactical factors, and the number of facilities in a strategic level are developed. Furthermore, 3 numerical example is provided to examine different conceivable outcomes.

Keywords: Additive manufacturing, Modelling, Optimization, Supply chain, and Fuzzy logic.

INTRODUCTION:

Additive manufacturing was not widely accepted and used at the beginning of its introduction. This technology was only used as a prototype due to its lack of recognition and lack of interest. But with the introduction of processes, materials, software and controls, the game changed. This rapid development has occupied many areas and the need for knowledge in this field seems obvious (Gebhardt & Hötter, 2016). In fact, the rapid enrichment of additive manufacturing technologies is along with an increase in the variety of materials, low-cost machines and the possibility of application in different fields. This leads to a fundamental lack of guidelines and standards (Gao *et al.,* 2015). Fortunately, the market has called for more advanced procedures as well as sustainable approaches, where AM can be the best solution. Additionally, if the current investments in this technology continues, we will see around 50 percentages of all goods manufactured by AM by 2060 (Dzogbewu *et al.,* 2022).

Despite the fact that there has been a lot of considerations about the costs, business models, capacities and characteristics of additive manufacturing in the literature, the impact of location-allocation of additive manufacturing factories and their construction in the supply chain has rarely been studied. Creating additive production facilities in the existing supply chain is an important field of study

(Mashhadi *et al.,* 2015). Gress and Kalafsky, (2015) emphasized on creating additive manufacturing in the value-added chain. Our research is one of the few efforts that has considered this impact on supply chain and operations. This is necessary and therefore very likely that this technology can affect many areas of life with its widespread usage. Based on this, there is a noticeable trend on the implementation of this technology in large industries such as aerospace, medicine and automobile manufacturing. In contrast to its benefits, additive manufacturing cannot totally conquer conventional productions. All in all, the need to enter this interesting technology seems to be a necessity (Attaran, 2017). And for this reason, it is very important to plan strategically and systematically.
In general, revolutionary technologies are seen as a negative phenomenon in the opinion of existing factories. This is due to the general trend against changes in industries. In order to overcome this problem and also to the advantages of not only traditional production, but also additive production, we have proposed a subtractive-additive production in the supply chain (Dzogbewu *et al.,* 2022). Additive manufacturing is based on increasing materials layer by layer of to build the final materials. This is necessary to strategically meet the requirements of the production comprehensively. In this paper, we look at the production holistically.

Attaran, (2017) tried to consider the current competition, where factories engage in an innovative production and production in large numbers with the ability to meet the specific needs of customers, which additive manufacturing can easily satisfy this. In addition, this production will have a major impact on the supply chain and specifically on logistics, which must be carefully studied. In short, it can be declared that this technology leads to the improvement of the chain and reduces the costs of distribution, assembly and transportation. It can be acknowledged that this technology will gradually enter in various industries and it has already indicated its potentials in many industries including aerospace, automobile manufacturing, industrial goods, customer specific goods, defense, architecture, health system, etc. In the past, due to the high cost of the supply chain and the 5% impact on costs, manufacturing factories turned to Radio Frequency IDentification (RFID) technology in 2000, and now it's time to reduce supply chain costs by emphasizing on additive technologies. In fact, it can be stated that the decade of 2010 is another decade of 3D printers and continues substantially. In the aforementioned research, both activities are focused on reducing supply chain costs, and it is clearly mentioned that additive technology can reduce complexities in general. These complications range from inventory complications to assembly complications and so forth. Additive manufacturing has many advantages over traditional manufacturing, four of which include cost, quality, speed and environmental effects. In short, we can say that additive technology has many effects on the supply chain; including accelerated product development, reducing the size of the economic package, increasing production flexibility and reducing waste. Practitioners who turn to additive manufacturing can reap other benefits, according to the sated study, from materials sourcing to logistics and distribution. The aforementioned research states that an interdependent supply chain in the global space with local production is one of the results. Additionally, as mentioned, many models will investigate additive technology in the future. These models will have the ability to reduce costs, reduce the time of sending goods and send goods on time and efficiently. These models will be associated with simplifying and effective supply chain networks by reducing the need for storage and inventory capacities, but our model is of the ones which study the supply chain systematically.

New technologies such as AM should be widely researched in many developing countries to be well-applied. Although South Africa has been able to benefit these advancements due to its cultural structure and cooperation between research and industry, what we try in this research is to introduce a very systematic approach to help all countries be better able to use this new paradigm, i.e., AM (Dzogbewu *et al.,* 2022). Therefore, in our research, an attempt has been made to fulfill all these needs in the fuzzy space, considering the uncertainty in reality, then a model has been proposed and it has been optimized. In addition, the research has well taken into account the production requirements in the supply chain space where both production types are possible. The main question of our work is if according to the uncertainty in the chain, including demand, receiving and sending, among others, it is possible to provide a suitable model for optimizing system costs, and if such a model is developed, how it is possible to solve and present appropriate proposals in a small and realistic environment. At the same time, by briefly dividing the research into part by part, the necessary material has been provided for researchers and managers to better understand the model and how to use it in practice. Research objectives include general and specific objectives. The general objectives of the research are divided into two strategic and operational objectives. The strategic goals of the research include modeling and locating traditional and additive facilities. Operational goals are the optimal use of production machines in each factory, the amount of transportation in the supply chain, and the amount of stock in each facility. At the same time, other goals are considered besides these goals; such as introducing and identifying different types of additive manufacturing technologies, identifying hybrid production, characteristics of additive manufacturing supply chain, etc. The current article is organized into three remaining sections. First, we will explain the keywords along with the literature review. Followed by the research methodology provided for analysis. At the end, we will finish the discussion by providing future direction, limitations and suggestions.

Review of Literature

Additive Manufacturing

In our research, additive manufacturing refers to manufacturing processes in which materials are deposited or melted layer by layer to reach a perfect shape or very similar (Spalt & Bauernhansl, 2016; Strong *et al.,* 2018). Hall of the 3D Systems Group created the first 3D printer in 1984. He named the machine Stereo lithography Apparatus (Attaran, 2017; Diegel, 2014). At the same time, its idea dates back more than 100 years. Its first patent for a method of producing geological maps by separating wax sheets and stacking them belongs to Blanner in 1982 (Rietzel *et al.,* 2017). Since then, an evolutionary progress has been observed in this field. Additive manufacturing includes various stages. These stages include the design stage, which is mostly with CAD date, afterwards is the stage of material selection and performance analysis. The next steps are completed by sending information from a computer to the printer to increase the material based on the given coordinates and analyzing the previous steps. The first layer is printed and then the remaining layers are printed to form the final product. STL (stereo lithography or standard language) is a standard file format that is used in various additive manufacturing machines, among other formats such as Sterio Lithography Interface (SLI), Systems Layer Contour (SLC), Hewlett-Packard Graphics Language (HPGL), Common Layer Interface (CLI), Virtual Reality Modeling Language (VRML), 3D Manufacturing Format (3MF), and Initial Graphics Exchange Specification (IGES). International Standards Organization (ISO) and American Society for Testing and Materials (ASTM) has introduced seven different sectors for additive manufacturing technologies (Gao *et al.,* 2015; Lee *et al.,* 2017).

The most commonly modeled processes in additive manufacturing are related to Stereo lithography (SLA), after which are Selective Laser Sintering (SLS), Selective Laser Melting (Manufacturing) (SLM), and Fused Deposition Modeling (FDM). Most authors deal with modeling of accuracy or reliability; while a few predict the mechanical properties of the final materials and the total manufacturing time (Bikas *et al.,* 2016). Basically, SLA uses a light source to connect a pre-designed shape in liquid. On the opposite point, SLS involves heating the powder in the substrate and then melting the object (Kietzmann *et al.,* 2015). Here, the main difference in these methods includes the method deposit, melting and materials used. In other words, the techniques are classified into groups related to powder, liquid and solid. In addition, the accuracy of each technology is different. For example, SLA ranges from less than µm10 to MicroSLA, SLM, SLS, Digital Light Projector (DLP)/Film Transfer Imaging (FTI), FDM, Direct Digital Manufacturing (DDM), MultiJet Modeling (MJM) and 3DP from µm100 to µm400. But their number in practice is much richer than what was discussed and is based on the **Fig. 1**. Based on the methodology FDM is a common technology due to its low cost, simplicity and high-speed process. This method was initially used to print strings of polymers, which have also been used for other materials. FDM is basically used for rapid prototyping, while the mechanical characteristics and quality of printed parts are less compared to powder-substrate methods such as SLS and SLM. Adjacent powders are fused, melted or stuck together with the help of an auxiliary adhesive in powder-bed methods, which results in better accuracy but more cost and lower process speed.

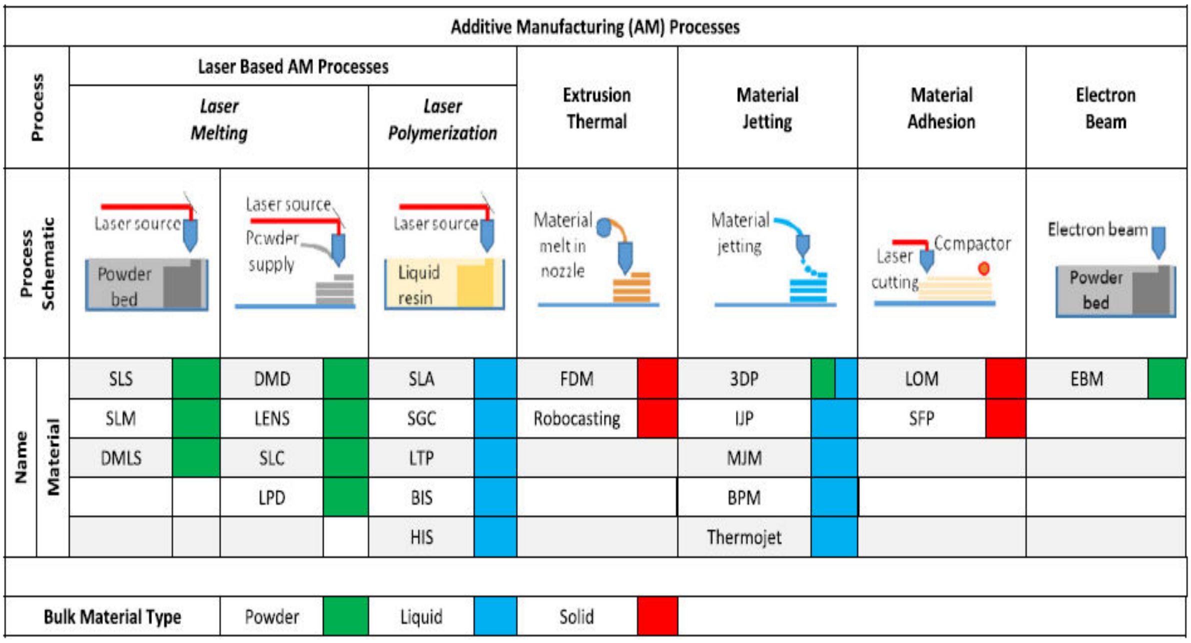

Fig. 1: Different categories of additive production based on types of construction materials (Bikas *et al.*, 2016).

Direct Energy Deposition (DED) uses an energy source (laser or electron beam) to melt iron powders, unlike SLM does not use any powder bed, and the raw materials are melted similar to FDM layer by layer with a very high energy to melt iron. Contour construction, which is dependent on material (concrete) output, is used to print large structures such as buildings. Stereo lithography is one of the first 3D printing methods, which is basically used for photopolymers that have the ability to produce parts with very good quality. Finally, Laminated Object Manufacturing (LOM) are based on cutting layer by layer and aggregation of sheets or rolls on top of each other. It is very important that many materials are used for additive manufacturing: plastic, resin, rubber, ceramic, glass, concrete and iron, each of which leads to different characteristics. In reality, there is not enough data for the actual operation of the processes and we need real and experimental information about the machines to apply one study to another. This technology has experienced many evolutionary phases. This started from prototypes for complex parts in industries, led to mass customization, which was accompanied by development in technology and parts were produced in small batch sizes, and finally was ended with acquisition and production of parts at home. In this regard, the last steps lead to more efficient use of human resources, more reliability, nature-friendly productions and more flexibility.

It is obvious that this technology cannot answer all the needs of the industry, and for this reason its disadvantages are as followed:

1) Limitation in the choice of materials, colors and surfaces
2) Higher cost in large productions
3) Limited strength and durability against heat, movement and color
4) Limited dimensions of the product
5) Less precision compared to other technologies
6) Ambiguous production of risky items
7) Problems of feasibility and intellectual property
8) Software support
9) Continuity and reliability
10) Quality assurance (Chua *et al.,* 2017).

In addition, financial services, professional business services, telecommunications, internet-based industries, retail, hospitals, entertainment, media, music and other service industries cannot be produced and therefore are not related to this technology. Additive manufacturing has a small application in energy production, for example electric and nuclear, as well as industries involved in the development of organic materials (Hannibal & Knight, 2018). To a large extent, the limitations of traditional production, such as the limitations of dimensions and costs of production in small dimensions, when talking about additive manufacturing, are related to the past technologies. This is due to the fact that additive manufacturing has many advantages over traditional manufacturing, which can be used in complex dimensions, and in this matter, we can add other pros such as fewer costs, customizing users at no additional cost, the ability to recover materials and the cost efficiency of parts in small dimensions.

Hybrid processes

We start by mentioning this sentence from Silva *et al*. in (2013):

"Additive manufacturing is not going to replace traditional processes. However, it will work seemingly, at least in the near future." Due to the benefits of additive production and traditional production, we have estimated that the transportation of parts from traditional production factories to additive production and vice versa will take place in the supply chain, thanks to which we increase the advantages of both factories and was used similarly to Flynn's work in 2016. Each of additive manufacturing and traditional manufacturing have disadvantages when considered separately. Hybrid production provides both advantages and new possibility. Lee *et al.* (2017) was able to achieve this goal in their efforts by introducing step-by-step hybrid production, energy, resources and environment. AM is considered to be advantageous in the supply chain, since it improves the supply chain costs and enhances sustainability, yet, we need to evaluate the costs associated and current lack of knowledge in this field (Calignano *et al.* 2023). Here, it is of critical significance to clarify what we mean by a hybrid process. As mentioned briefly, hybrid productions use both subtractive and additive processes simultaneously. This provides the benefits of both processes in production; that is, the complexity of additive production and the appropriate quality of the level of traditional production (Du *et al.,* 2016; Gebhardt *et al.,* 2016; Gibson *et al.,* 2015; Newman *et al.,* 2015).

More precisely, based on each aspect of the technologies, we are given the opportunity to choose the most appropriate choice. If, for example, the process has a large volume to cut and/or the material is very expensive, additive manufacturing is very useful as long as the lifespan is considered. In this case, traditional production can help to form a suitable product with the combination of additive production. The cell interaction in a hybrid system should be very strong to be able to control the various processes in the machines and to be able to manage the related data in the system. The control system must have the ability to manage the sequence and improve the processes in the whole chain so that the operation is in an efficient and agile mode. In our model, a hybrid production is proposed due to its rich advantages. It should be mentioned once again that hybrid production is a combination of additive and traditional production that is used sequentially or in an integrated mode, including a fixed base and a direction controller to shape the parts. This method has been used to increase the accuracy of dimensions and improve the entire production process. In addition, the problem of producing complex areas, i.e., where one process (reductive or additive) is not enough, is solved with hybrid technologies. Li *et al.* (2017) considered the integration of additive and subtractive manufacturing, especially for end-of-life products, to strategically and systematically produce new parts without any recycling. Their attempt led to the reduction of energy consumption, resources and environmental benefits. In 2018, it was studied by Bandyopadhyay *et al.* that a hybrid production with the possibility of using Wi-Fi and prefabricated components improve production by reducing waste. In addition, in the same year, Kaspar *et al.* (2018) benefited from a comprehensive and integrated view of a hybrid production and materials, processes and goods, and all of them were considered at the same time by means of a chart. In their study, more systematic considerations were also requested for further research. A structural comparison between traditional and additive processes allows us to have a suitable application. The first thing is that every technology has its own advantages that need to be applied carefully. For example, complex components must be manufactured by additive manufacturing. The second, states that some processes cannot be compared equally; for example, some cases require about twenty processes that can be combined with an additive process. In the end, innovation is a suitable result of additive production, which is very limited in traditional production. In the literature, there are various methods for the hybrid processes. In this research, the possibility of production planning has been given to the designer. In a nutshell, we can assert that all the possibilities of designing traditional production at the beginning and adding materials with additive production, using robots to combine processes at the same time or using reduced production as the only post-processing of the process have been left as free decisions. A good hybrid method is characterized by its ability to combine additive and subtractive sequential processes. This topic is an important research area for machine designers to improve hybrid production. The flow of materials and information are among other important decisions. The main challenge for the integration of additive and subtractive manufacturing in current hybrid methods is the need for a hybrid process planning protocol for the post-processing of additive manufacturing, which represents the different nature of the additive manufacturing process (material erosion, layer thickness, direction, etc.), machining (tool design, the amount of machining, etc.) and the specific features of the part (main features and tolerance requirements). As part of the model, post-processing is recommended to be done whenever possible by a traditional factory. Similarly, parts produced in traditional factories can also be produced in additive manufacturing factories.

Role in the supply chain

Additive manufacturing has the ability to change the entire supply chain and can eliminate many unnecessary processes. The supply chain has become known as "global-local". In other words, parts are produced with high interaction between customers and producers, while information can be exchanged between them and a smaller inventory can be stored with higher responsiveness. This is called reshoring shift in the view of Calignano *et al.* in (2023). In fact, the supply chain has changed dramatically with the introduction of additive manufacturing. In 2013, Liu *et al.* used a supply chain operations reference model to analyze the impact of aircraft spare parts supply chain integration and achieved savings, especially in terms of costs and inventories. In their study, it is also mentioned that the number of steps can be reduced in comparison with traditional productions. In addition, additive technology provides the ability to redesign products with fewer parts and closer to customers. In order to fully understand the integration of additive and subtractive processes, a holistic view of the requirements of these processes is essential. A similar study was conducted by Ford *et al.* (2016) and they noted that investigating additive production is very necessary and every study is associated with a gap in knowledge and practice. Here, we need to respond to questions such as the structure and network of the supply chain and intermediate parts in the chain network. Additive manufacturing should be seen as a transitional technology. This causes multiple transitions of production items. This causes the transition of traditional business models. This will change existing supply chains. It also causes the transition of economy of place, manner and time of production of objects. Gao and Attaran, (2013, 2017) noted considerable impacts in industrial, assembly and supply chain industries, respectively. Kitzman *et al.* (2015) claimed that 3D printing enables just-in-time manufacturing and Kanban systems for factories by eliminating unnecessary inventory. From the point of view of an industrial supply chain, many effects were observed in the warranty of service components, repairs and return of goods. In 2017, reductions in cost, carbon dioxide emissions, and transportation were observed by Chuva *et al.* This issue was also investigated by Ayers et al. in the same year that a systematic view is required for the integration of all systems involved in the production of final parts. Thus, this issue should be noted that the production is performed in a holistic perspective, and internal systems and the environment should be considered as a supply chain network. In this respect, the only difference is that the post-processing responsibility is assigned to the traditional factory to improve the value chain. These facts were emphasized by Hannibal and Knight, (2018) who state that even on a global scale, the need for a local and widespread additive production does not change, yet the use of this technology, especially in developing countries is different, with regard to the economical limitations. This importance was also added by Hannibal and Knight that the entire logistics network can be changed with shorter connections and simplicity.

Furthermore, this is essential to consider sustainability factors so that competitive, economic, social and more importantly environmental aspects can be achieved simultaneously. In the literature by Al Muslimi in 2018, several methods to achieve these strategies was proposed, based on the reduction of materials, energy and waste. This subject was taken into account by more independent energy-consuming products and better information flow. In addition, key attributes are very important for all companies. These items are considered separately by the companies, but they all lead to quality and sustainability. A supply chain is a combination of supply components from suppliers to final consumers and all members under considerations, when we talk about additive supply chains. To be more precise, the benefits for this change are countless, some of which are gathered in **Table 1**.

Table 1: Four basic parts of the application of additive manufacturing.

Key factors	Advantages
Costs reduction	Reducing the amount of economic order, inventory, packaging and...
Fast response	Reducing ordering time, interventionists, changes and...
Quality improvement	Reducing waste, participating in customer feedback, managing demand uncertainty and...
Environmental effects	Improving sustainability, reducing carbon effects, reducing traditional production waste and...

From the table and from the point of view of a production system, it can be concluded that the supply chain will be significantly more lean and agile and at the same time lean and agile. Material performance, parts flexibility, fast ordering and less waste make additive production capable of being lean and agile at the same time. In addition, it is predicted that the whiplash effect in the supply chain will decrease with additive production. In general, additive manufacturing affects the supply chain from product design, machine design, production line design, and facility design to the design of the entire supply chain. By using AM in the chain network, it is necessary to consider all the advantages, which are sometimes very difficult to measure and count. This is because AM eliminates many unnecessary steps and therefore it is necessary that the models show all the advantages and uncertainties in the supply network. In fact, it is easily noticeable that AM can affect every step of the chain. In addition to integrating the entire chain network, additive manufacturing can remarkably integrate assembly activities into one step. For example, a robotic system that requires many parts to be assembled to make the final product can be produced in one stage. Logistics is another issue that can be shaped differently by incremental production. In general, closer communication is observed along with customized mass production at a lower cost. Indeed, the market will be closer to the customers and many of the current and unnecessary processes will be removed.

Logistics are affected as below:

1) Mass ordering results in reducing inventory levels and warehouse requirements.
2) Goods that are produced in other countries can be produced locally, leading to a reduction in transportation.
3) The production process is amazingly done by only one facility. Therefore, logistics providers will be less involved in upstream supply chains.
4) There will be a change in procedure from push supply chains to pull supply chains. Long productions for mass production (economic order point) are replaced by limited mass order productions and customized products (economy of scope).
5) Manufacturers will have a better ability to respond quickly to customer demands.
6) There will be less work-in-process inventory and less finished goods in the warehouse and in transit, which will reduce the overall costs of the supply chain system.
7) One of the first sectors that is affected by additive manufacturing technologies is the logistics sector of parts services. Additive manufacturing can order the design of parts services in a short period of time and can eliminate the huge amount of rework that is wasted in opening parts in supply chains (Attaran 2017; Rahman KS., 2021).

All of the mentioned literatures clearly emphasize a holistic view of the supply chain for facility integration. This issue was mentioned by Hannibal and Knight (2018), who emphasized on reconsidering value chains and traditional productions and a need to replace local and customized productions. Based on this, an AM supply chain model has been introduced by the authors to be a strategic and operational guide for decision making.

Fuzzy Logic

According to the systems perspective, expressed by Ayers *et al.* (2017), it is implied that fluctuations in the chain should be considered. Although there have been many views to deal with these uncertainties; For example, stochastic models, gray method, robust optimization, etc., the fuzzy method is a very effective method that helps managers to control these uncertainties; therefore, it is used in our model to achieve aforementioned desired goals. Another reason for using fuzzy logic is that it takes linguistic variables into consideration, which is a very important advantage in modeling. It should be noted that fuzzy logic deals with these problems easily with membership degree of each variable between 0 and 1.

Related literature

Until now, most of the literature has emphasized on the cost analysis of the application of Additive Manufacturing. But in 2014, Mellor *et al.* emphasized on the analysis of location. In addition, Mashhadi, Esmaeilian, and Behdad, (2015) broadly stated which literature is available in this field and then provided two case studies in supply chain analysis with simulation methods and dynamic systems. In their research, order time reduction was the result of an agent-oriented simulation and reduction of the whiplash effect of the results of dynamic systems. Scott *et al.* (2015) presented a holistic model for analyzing the whole chain in a stochastic space. These examples are great improvements for practitioners to decide which production technology to use. In addition, it was observed which factors had an essential role in acceptance; which are demand, cost of materials, among many others. In the following year, 2016, a deterministic model was developed by Barez *et al.* this model included a two-stage supply chain network node and tried to minimize costs of the whole chain. Afterwards, an analysis of the US iron supply chain was conducted by Strong et al. In this research, the optimal number of AM hubs in the chain with the help of locating facilities without capacity and mean-location analysis was observed. The processes here were considered hybrid; which is because, for example, the parts were processed in the traditional factory.

METHODOLOGY:

In this research, random numerical examples have been used to test the accuracy of the model. First, we will introduce the sets and parameters of the model and then present the model with the description of the de-fuzzification method. In the end, we use GAMS 25 software to solve the examples and we will analyze the results.

Symbols and signs

Sets

$a \in A$ Set of AM factories

$c \in c$ Set of customers

$i \in I$ Set of products

$p \in P$ Set of traditional factories

$s \in S$ Set of suppliers

$t \in T$ Set of time intervals

$w \in W$ Set of warehouses

Parameters

Demand

$demand_{cit}$ Demand by customers for each product (fuzzy)

Production

$mfg\_capacity_{pit}$ Traditional factory capacity

$mfg\_var\_cost_{pit}$ Variable cost of traditional factory production (fuzzy)

$mfg\_oper\_cost_{pit}$ The operational cost of traditional factory production workshop (fuzzy)

$mfg\_open\_cost_{p}$ The cost of opening a traditional factory

Distribution

$wh\_var\_cost_{wit}$ Variable storage cost (fuzzy)

$wh\_oper\_cost_{wit}$ Warehousing operational cost (fuzzy)

$wh\_open\_cost_{w}$ The cost of opening the warehouse

$supplier\_capacity_{spit}$ Capacity of suppliers (fuzzy)

$supplier\_cost_{spit}$ Supplier unit cost (fuzzy)

Additive manufacturing factory

$am\_mach\_hours_{at}$ The set of production hours of the product unit

$am\_cap\_usage_{it}$ AM machine capacity

$am\_mach\_oper\_cost_{ait}$ Operating cost of AM machine

$am\_mach\_purch\_cost_{ait}$ The cost of purchasing an AM machine

$am\_mat\_cost_{t}$ Cost of raw materials per kilogram of AM factory (fuzzy)

$am\_mat\_usage_{it}$ The amount of consumption per product of AM

$am\_open\_cost_{a}$ The cost of opening AM

$am\_var\_cost_{ait}$ Variable cost of AM (fuzzy)
Transportation
$am\_trans\_cost_{acit}$ Transportation cost from AM to customers (fuzzy)
$asm\_trans\_cost_{apit}$ Transportation cost from AM to traditional production (fuzzy)
$ib\_trans\_cost_{pwit}$ Transportation cost from traditional factory to warehouse (fuzzy)
$ibs\_trans\_cost_{pait}$ Transportation cost from traditional factory to AM (fuzzy)
asm_status_{apit} Binary variable transition from AM to traditional factory
ibs_status_{pait} Binary variable transition from traditional factory to AM
$ob\_trans\_cost_{wcit}$ Transportation cost from warehouse to customer (fuzzy)
$supply\_trans\_cost_{spit}$ Transportation cost from supplier to traditional factory (fuzzy)
Inventory
$am\_start\_inv_{ait}$ Initial inventory of AM
$inventory\_hold\_cost_{i}$ Inventory holding cost (fuzzy)
$mfg\_start\_inv_{pit}$ Traditional factory initial inventory
$wh\_start\_inv_{wit}$ The initial warehouse inventory
inf A large number
Decision variables
am_open_{a} Binary variable for additive manufacturing location
$am\_oper\_machines_{ait}$ Integer variable for the number of additive manufacturing machines running
$am\_purch\_machines_{ait}$ Integer variable for the number of AM machines
mfg_open_{p} Binary variable for traditional factory location
$mfg\_operating_{pit}$ Binary variable for traditional factory running machines
wh_open_{w} Binary variable for warehouse location
$wh\_operating_{wit}$ Binary variable for warehouse operations
am_flow_{acit} Flow rate from AM to customers
ib_flow_{pwit} Flow rate from traditional factory to warehouse
ibs_flow_{pait} Flow rate from traditional factory to additive manufacturing
ob_flow_{wcit} Flow rate from warehouse to customers
asm_flow_{apit} Flow rate from AM to traditional factory
$supplier\_flow_{sait}$ Flow rate from supplier to AM
$am\_ending\_inv_{ait}$ Ending inventory of AM
$am\_production_{ait}$ AM production rate
$mfg\_ending\_inv_{pit}$ Traditional factory ending inventory
$wh\_ending\_inv_{wit}$ End stock of the warehouse

Model

$$\min z = \sum_a am\_open\_cost_a * am\_open_a + \sum_a \sum_i \sum_t am\_mach\_oper\_cost_{ait} * am\_oper\_machines_{ait} + \sum_a \sum_i \sum_t am\_mach\_purch\_cost_{ait} * am\_purch\_machines_{ait} + \sum_p mfg\_open\_cost_p * mfg\_operating_p + \sum_p \sum_i \sum_t mfg\_oper\_cost_{pit} * mfg\_operating_{pit} + \sum_w wh\_open\_cost_w * wh\_open_w + \sum_w \sum_i \sum_t wh\_oper\_cost_{wit} * wh\_operating_{wit} + \sum_p \sum_w \sum_i \sum_t ib\_trans\_cost_{pwit} * ib\_flow_{pwit} + \sum_w \sum_c \sum_i \sum_t ob\_trans\_cost_{wcit} * ob\_flow_{wcit} + \sum_w \sum_c \sum_i \sum_t wh\_var\_cost_{wcit} * ob\_flow_{wcit} + \sum_p \sum_w \sum_i \sum_t mfg\_var\_cost_{pwit} * ib\_flow_{pwit} + \sum_s \sum_p \sum_i \sum_t supplier\_cost_{spit} * supplier\_flow_{spit} + \sum_a \sum_i \sum_t am\_var\_cost_{ait} * am\_production_{ait} + \sum_a \sum_i \sum_t am\_mat\_cost_t * am\_mat\_usage_{it} * am\_production_{ait} + \sum_w \sum_i \sum_t wh\_ending\_inv_{wit} * inventory\_hold\_cost_i + \sum_p \sum_i \sum_t mfg\_ending\_inv_{pit} * inventory\_hold\_cost_i + \sum_a \sum_i \sum_t am\_ending\_inv_{ait} * inventory\_hold\_cost_i + \sum_p \sum_a \sum_i \sum_t ibs\_trans\_cost_{pait} * ibs\_flow_{pait} + \sum_a \sum_p \sum_i \sum_t asm\_trans\_cost_{apit} * asm\_flow_{apit}$$

Equation (1)

st:

$$\sum_w ib\_flow_{pwit} - mfg\_start\_inv_{pit} - mfg\_ending\_inv_{pit-1} \le mfg\_capacity_{pit}$$

Equation (2)

$\sum_w ob\_flow_{wcit} + \sum_a am\_flow_{acit} \geq demand_{cit}$

Equation (3)

$wh\_starting\_inv_{wit} * wh\_operating_{wit} + \sum_p ib\_flow_{pwit} - \sum_c ob\_flow_{wcit} + wh\_ending\_inv_{wit-1} = wh\_ending\_inv_{wit}$

Equation (4)

$\sum_c ob_{flow_{wcit}} \leq wh_{operating_{wit}} * inf$

Equation (5)

$\sum_i \sum_t wh\_operating_{wit} \leq wh\_open_w * inf$

Equation (6)

$\sum_w ib_{flow_{pwit}} \leq mfg_{operating_{pit}} * inf$

Equation (7)

$\sum_i \sum_t mfg_{operating_{pit}} \leq mfg_{open_p} * inf$

Equation (8)

$\sum_s supplier\_flow_{spit} + \sum_a asm\_flow_{apit} + mfg\_starting\_inv_{pit} + mfg\_ending\_inv_{pit-1} \geq \sum_w ib\_flow_{pwit}$

Equation (9)

$am\_start\_inv_{ait} * am\_open_a + am\_ending\_inv_{ait-1} + am\_production_{ait} - \sum_c am\_flow_{acit} = am\_ending\_inv_{ait}$

Equation (10)

$am\_production_{ait} * am\_cap\_usage_{it} \leq am\_mach\_hours_{at} * am\_oper\_machines_{at}$

Equation (11)

$am\_oper\_machines_{at} - am\_oper\_machines_{at-1} = am\_purch\_machines_{at}$

Equation (12)

$\sum_i \sum_t am\_oper\_machines_{ait} \leq am\_open_a * inf$

Equation (13)

$asm\_flow_{apit} \leq asm\_status_{apit} * inf$

Equation (14)

$ibs\_flow_{pait} \leq ibs\_status_{pait} * inf$

Equation (15)

De-fuzzification

Due to the triangular fuzziness of some parameters in the objective function, we de-fuzzified them using the following formula.

$c_j = \frac{(cp,4cm,co)}{6}$ ∀ j (Shondi 2016)

Equation (16)

By defining the following variables:

pi = The amount of tolerance for $demand_{cit}$

bi = $demand_{cit}$

To de-fuzzify the demand that is in one of the constraints the following algorithm has been used.

max λ

st:

$\lambda(z_u - z_l) - cx \leq -z_l$

$\lambda p_i + \sum_j a_{ij} x_j \leq b_i + p_i \; \forall i$

other non-phase constraints

Equation (17)

Equation (1) seeks the minimum possible costs regarding the model, the sum of all possible costs. Equations (2) to (15) are all constraints of the model, guaranteeing the logic of the model. Finally, equations (16) and (17) is the algorithm we used to de-fuzzify our fuzzy equations.

RESULTS:

Numerical examples in GAMS 25 optimizer software have been developed to address the functionality and accuracy of the model. **Table 2 - 4** and **Fig. 2** briefly show the results. In this research, first these examples are presented in a non-fuzzy environment. Then, the objective function of formula number 1 in the last chapter has been de-fuzzified. At the same time, upper and lower bounds are defined for the demand constraint, which are shown as zu and zl respectively. In the next step and at the end, relations number 2 have been used to determine the minimum operational and strategic costs of the objective function, taking into account all the predefined restrictions.

Table 2: Collections.

Number of warehouses	Number of time intervals	Number of suppliers	Number of traditional factories	Number of products	Number of customers	The number of AM factories	Collections
1	1	2	5	10	5	2	Amounts

Table 3: Demand in comparison to outputs.

Very low	Low	Very much	Demand
1	2	2	am_open
2	5	5	mfg_open
20	50	50	mfg_operating
1	1	1	wh_open
10	10	10	wh_operating
4	12	12	am_oper_machines
4	12	12	am_purch_machines
6	22	28	am_flow
20	50	50	ib_flow
0	0	0	ibs_flow
48	50	10	ob_flow
0	0	0	asm_flow
20	50	50	supplier_flow
0	0	0	am_ending_inv
4	12	12	am_production
0	0	0	mfg_ending_inv
0	0	0	wh_ending_inv

Table 4: The amount of demand and its effect on the ratio of increasing to decreasing production.

Very low	Low	Very much	
0.5	0.4	0.4	AM/TM ratio

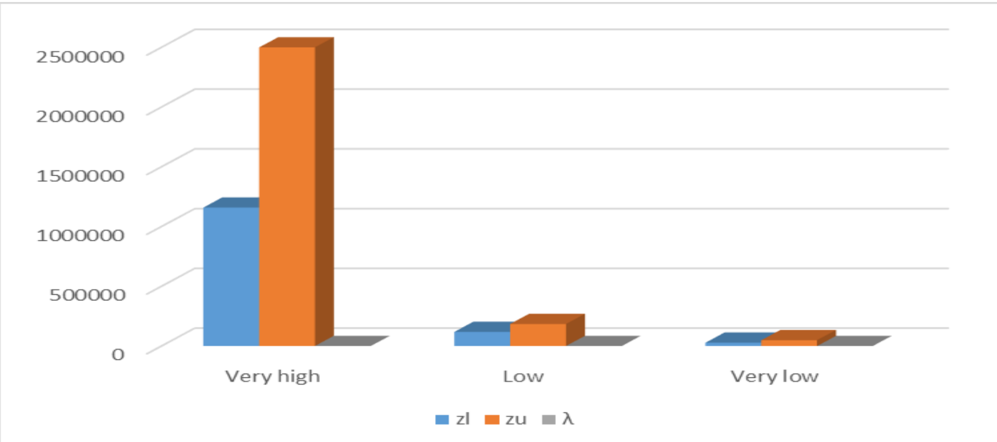

Fig. 2: Objective functions and demand.

DISCUSSION:

From the resulting tables in the previous chapter, it can be predicted that, with the decrease in demand, a greater number of AM factories will be used in comparison with traditional production. This is because AM has the ability to respond to low-volume demands at a lower cost and faster. However, it should always be considered that by improving the supply of raw materials and lowering its costs, better benefits can be achieved; Among them, lack of dependence on traditional production and cheaper production in high scales;

a vast research area for future directions. Additionally, the developed model showed that it is possible to analyze the data precisely and simply with linguistic variables. This model shows us that it is not difficult to reach an optimal solution in the supply chain according to the amount of variable demand, among other variables. The functionality of the model was shown with examples in different dimensions. Yet, it is obvious that considering the existing limitations, it is recommended that this effort be evaluated in reality and with more extensive data.

CONCLUSION AND RECOMMENDATIONS:

The presented model has the ability to calculate in different dimensions. The model can also evaluate data in different time periods. This is especially useful for situations where we have to analyze the data in multiple steps and in different time periods. This problem can be considered as further research due to its breadth and complexity. Limitations of the research included, to a large extent, data limitations. In the conducted research, there was no standard available data. In addition, this field need a huge amount of investment to find a real case study. All in all, this model is a practical solution for all the enthusiasts of various industries to design their supply chain and take advantage of AM production. All models are completely practical and open the way for new technologies. As stated, it is suggested that people related to supply chain design and analysis, or any other title, can benefit from this research.

1. In the first case, it is suggested to use random fuzzy numbers to get a more accurate result.
2. Second, according to the practical nature of the research, standard or real data should be used.
3. Green supply chain is one of the new research areas. Therefore, for proper productivity and nature-friendly production, it is suggested to build green AM production.
4. Lateness and earliness are important and vital issues in many supply chains. Based on the costs of lateness and earliness, the presented model can be developed so that the costs of this field can be optimized.

AUTHOR CONTRIBUTIONS:

N.E. conceptualization, methodology, writing the manuscript, N.E.; and S.A.D. contributed in analysis, investigation, visualization. A.D. finally checked the manuscript and editing, and Formal Analysis. All authors who are involved in this research read and approved the manuscript for publication.

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CONFLICTS OF INTEREST:

The authors declared obviously in the manuscript and have no conflict of interest.

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