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An Integrated Value-Addition in Supply Chain Network for Metal-based Additive Manufacturing

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Abstract

The increasing speed of product development and the ability to deliver complex, near-net-shaped engineering metal parts are key benefits of additive manufacturing (AM). Producing or replacing parts by leveraging AM relies heavily on supply chain (SC) functions. Inadequately managed SC could lead to lower productivity and process waste. Hence, the aim is to integrate value-adding activities into the SC network using the principles of lean manufacturing, such as Value Stream Mapping (VSM) and flowchart. A case study of a braking system manufacturer company in South Africa was used to exploit VSM and the flowchart for reducing process waste. The result of the case study revealed that the frequent use of expedited shipping increased transportation costs and lead times required excess raw material inventory, and lengthy supplier order processing. The approach demonstrated the need to adjust the business model by virtually synchronising the flow of information across the SC players in the configuration of the entire AM production and distribution activities. The study provides a framework that can guide AM organisations in improving efficiency and achieving significant cost and time savings.

Keywords: Additive Manufacturing; Supply Chain; Metal Components; Lean Principle.

1. Introduction

Disruptions in the supply chain (SC) and the dynamics of customer demand drive the need to implement smart manufacturing systems for metallic part production. Additive Manufacturing (AM) is an advanced manufacturing system in the context of Industry 4.0. AM allows the fabrication of parts on demand, using a layer-by-layer building process to create a part from a 3D computer-aided design (CAD) [1]. Generally, the AM process is divided into two phases: the digital process and the physical production. On the one hand, the digital phase includes the CAD design, pre-processing, and in situ processing steps. On the other hand, the physical steps involve processing and post-processing [2]. These steps simplify the conventional value chain by eliminating the need for prototyping, storage, and diverse supplier networks [3]. The value creation in AM is derived from the reduced SC process [4]. In addition, the AM uses a "market-to-order" strategy to ensure responsiveness to increasing market demand [5]. This entails that the fabrication of parts is dictated by the end-user order. This creates value for the end users and ensures agility and visibility for the downstream SC [6]. Fig.1 presents the conventional and AM SCs (highlighted in red), wherein the AM brings the manufacturers closer to the end users, which removes the

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transportation between manufacturers and wholesalers, then to the distributors, before reaching the end user.

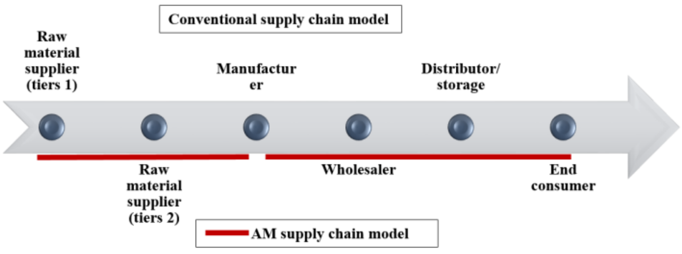

Fig.1. Supply chain models comparison: conventional vs AM adapted from [4].

Several studies [4, 7-9] have highlighted the impact of AM on SC configuration and performance. In the consolidation of complex geometrical metallic parts, AM allows the production of the part as a single component, removing the need for assembly and the product's bill of materials. Thus, reducing the number of suppliers, workforce, materials, and transportation requirements [9]. AM significantly reduces the level of inventory for raw materials and final products [10]. The reduced SC networks in AM scale down the SC lead-time by up to 60%, as found by [11]. While there is evidence that AM creates value by shortening the SC, the shortcoming of the technology, as discussed in the literature [12, 13], is experienced in the mass production of metallic parts. The lack of repeatability affects reproducibility and high quality assurance procedures at the downstream end of the process chain [14]. Other limitations include the restricted choice of raw materials, the production costs compared to conventional manufacturing (CM) processes, and the cycle time [15-16]. Moreover, an empirical investigation conducted by interviewing about 51 enterprises on the impact of AM on SC was carried out by Noorwali et al. [8]. The study reveals that there are uncertainties related to the reduction in the number of suppliers for AM. The SC network for raw materials is a consequence of key strategic decisions related to the location and transportation of raw materials and hardware. The lack of value-addition results from the absence of having products available when required. One approach developed was a model of value system integration wherein the supplier networks could be shortened through collaboration between AM machine manufacturers and users [17]. A successful implementation of AM is a driver of higher business value in terms of availability and lead-time [11]. Moreover, previous studies investigated the AM value chain in line with the flow of information between suppliers and manufacturers [18-19], using decision-making approaches without considering the physical process chain that involves the procurement of raw materials and AM hardware. This often entails waste elimination as a crucial aspect of efficient value creation.

Therefore, the purpose of the study is to integrate a value-added activity in the SC network for metal component production via AM. The proposed approach is focused on VSM and flowchart to increase productivity through the identification of waste. Given the complexity of the process chain [12], the study uses a case study scenario to propose a framework.

The remainder of the paper is arranged as follows: Section 2 provides an overview of the metals AM and AM SC. Section 3 discusses the need for creating value by integrating SC. The fourth section discusses the implementation of lean thinking in the AM SC using a case scenario. Section five concludes this paper and gives some recommendations for future work.

2. Metal additive manufacturing

2.1. Metal additive manufacturing technologies

The metal AM is categorised into seven different groups based on the thermal source and feedstock, as described in [20]. The outstanding category is laser-based technology, with the powder bed fusion (PBF) process accounting for 54%, the direct energy deposition (DED), and material/binder jetting each accounting for 16% of the metal AM market [20]. The PBF has known such interest due to its capabilities of producing highly complex geometries and its ability to accommodate a wide range of materials. Among Direct Metal Laser Melting (DMLM), Direct Metal Laser Sintering (DMLS) and Electron Beam Melting (EBM), Selective Laser Melting (SLM) is the PBF's most commonly used process [21].

Despite roadblocks encountered along the value chain of the technologies, the industrialization of metal AM has seen 20% annual growth [22].

2.2. Metal additive manufacturing process chain

The process chain describes the sequence of steps required to fulfil the AM user request [23]. In the context of PBF, the raw material for the feedstock is a metal powder which spherical morphology and particle size distribution of 40-60µm [14].

The digital process chain starts with the design creation on CAD software, which is thereafter converted into a standard triangle language file (STL). On the platform, the geometry and structure of the part to be manufactured are optimised [3]. The software allows the manipulation of parameters and the slicing of the part to determine the quantity of material and time required for production. Then, the G-code is sent to the AM hardware with a minimum amount of setup to undergo before fabrication of the part can start. Customers have the versatility and advantage of sending orders to the manufacturers through digital communication. There is real-time transparency in the SC [4]. This creates more value and fosters decentralised production.

At the physical level, the part building process is included, followed by post-processing operations such as cleaning of powder, removal of support structure, heat treatments (HT), and surface finish requirements to meet the specifications of the desired application [23]. These steps require tools that are not always readily available for purchase on the shelf. Hence, it calls for the selection of a supplier for sustainable procurement of the tools.

It is worth noting that post-processing, such as HT, is an area that still needs to be automated to reduce the delivery time and enhance the quality of the finished part's surface roughness [24]. HT such as T6 and hot isostatic pressing are expensive treatments that can be required according to the desired industrial application. A synthesised representation of the process chain with the different steps is seen in Fig. 2.

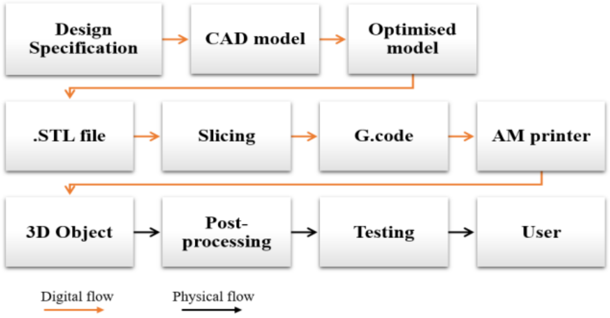

Fig. 2. Metal Additive Manufacturing process chain.

2.3. Additive manufacturing supply chain overview

There are four key points driving the value chain: software technologies, hardware technologies, materials, and services [22].

2.3.1 Software technologies

The design for AM is highly reliant on software technologies [18]. Factors such as geometries, topology optimisation, building orientation, and statistical accuracy of the mechanical properties are established through the design platform [6]. With the advanced and increased demand for customization, the market for software technologies has upgraded, with affordable software available for the application of AM [16]. Software is available for purchase online.

2.3.2 Hardware technologies

The hardware technology, also called AM equipment, requires a capital investment to start with production. Metal equipment continues to be more expensive than polymer technologies [22]. The flow of information between users and manufacturers has assisted in enhancing the operating systems of the machines. This requires the users to carefully evaluate the need for AM and to select the appropriate technology [15]. Moreover, metal AM machines include additional tools and equipment such as a sieving station, gas, appropriate vacuum cleaners, consumables, and nitrogen generators. Some of this equipment might not be readily available in some countries. Hence, there is a need for establishing a SC network.

2.3.3. Raw material

There is still development of new materials as the market for AM is growing [22]. In general, the AM process minimises material waste by recycling it. However, in the context of PBF, the powder degrades after a couple of re-uses. Then, the spheroidization of used powder becomes a critical step to avoid wastage of materials [25].

Moreover, the available AM powders such as titanium and its alloys, aluminium alloys, stainless steel and iron have yet to be fabricated in Africa [9]. Most African countries using AM have to request them from overseas, which takes a toll on small enterprises that want to adopt AM. Material is therefore a prerequisite before production orders are validated. The raw materials is of paramount importance, as the quality of the finished part is a result of their quality [26].

2.3.4. Services

The AM ecosystem is aware of a scarcity of skilled technicians who can effectively maintain the equipment [11]. Some countries, for example, in the Africa region, have a scarcity of experts in the field [25]. Moreover, inadequate knowledge and an unskilled workforce are threats to the successful application of AM. A lack of technical training can result in over processing and material waste.

3. Supply chain integration for value-creation

SC integration simplifies the complexity of SCs by establishing information sharing across all the touch points of the supply network involved in production [19]. A company learns to stay competitive and recognise demand patterns by knowing the SC complexity metrics.

Strategies to deal with complexity management can be applied to SCs to simplify AM production processes in any organisation. Table 1 presents the production technology-driven complexity metrics for value addition or not for AM and CM systems [27].

Table 1. Metric for comparing supply chain complexity in manufacturing techniques [27].

Area	**Metrics**	**Characteristics**	**Change from Conventional (CM) to additive manufacturing (AM)**	
			Value decrease	**Value increase**
Quality	On time delivery	Percentage of deliveries at promised time	CM	AM
	Performance	Customer requirements on delivery is met (time, quality)	CM	AM
Service	Flexibility to meet customer requirements	Weeks of product change	CM	AM
Cost	Supply Chain Costs	Total supply chain costs	AM	CM
	Capacity Utilisation	Machining capacity utilization	CM	AM
	Inventory turnover	Inventory turns per year	CM	AM
	Inventory days on stock		AM	CM
Lead time	Order cycle time	days required to process	AM	CM
	Supply chain cycle time	Days from order to delivery	AM	CM

4. Lean manufacturing principles in the additive manufacturing supply chain

4.1. Case study scenario

Company A started as a small organisation that supports the automotive and rail industries with brake components in Pretoria, South Africa. The company has grown to deliver steering knuckles and impellers (Fig. 3) using commercial PBF technology. The powders used for both components are aluminum (Al) alloys. Al alloys are lightweight materials that consequently influence the weight of the vehicle, its fuel consumption, and its performance.

a) Impeller **b) Steering knuckle**

Fig. 3. Company A additive manufacturing parts.

The case scenario is explorative and uses secondary data and direct observation to record data concerning the changeover time (C/O), the cycle time (C/T), the uptime, numbers of workers, value added time, number of shifts and lead time. From the company documentation, it was found that the sourcing of the powders is from Europe due to the unavailability of local production of Al alloys AM powder. The PBF machine was purchased locally to benefit from direct after-sale service. Design, modelling, topology optimisation, meshing, structural analysis, and slicing are all done with Autodesk inventor and magic software. Payments for software licences are renewed annually.

Considering the loading conditions (braking, fatigue, and buckling), mechanical testing is conducted through Finite Element Analysis (FEA) and at the post-processing level. Although the simulation is significant, the post-processing is considered a laborious step to improve mechanical properties and meet the application requirements. Post-processing follows the manual removal of the part, depowdering using a vacuum cleaner and a brush, thermal stress relieve, HT processes, and surface finish polishing. While the company always ensures that customer demands are met on time, the application of lean thinking is assumed to be provided by the nature of the technology. Hence, operators do not seem to look for ways to improve the process. The challenges encountered by company A are the lack of understanding of the full process chain and the limited visibility within their materials supplier and their procurement department. These increase the level of inventory as the company needs to replenish their stock more often due to importation and unexpected order processing issues. Additionally, there is a lack of expertise about the technology and post-processing procedures needed to achieve the necessary final product quality. Among these challenges, this paper addresses the understanding of the process chain by using lean thinking.

Lean thinking is summarised in five principles: understanding the value, designing the entire value stream, creating a flow, establishing pull system and seeking perfection. Among the five principles, the pull system is well implemented, as production only starts with a customer demand. In addition, understanding the value of AM is a topic that has been widely discussed. However, the value stream map and flowchart are less explored for standardisation and elimination of unnecessary activities.

4.2. Proposed approach and discussion

The VSM is an appropriate tool that clearly shows the flow of material and information, and describes the production system. Fig. 4 (a) depicts the current condition of the use of AM on the shop floor, while Fig. 4 (b) the future state of the VSM. The upstream of the maps shows the information flow and the flow for supplier; while the downstream depicts the material flow from production to customer. The timelines at the bottom of the maps depict the production lead time and processing time also known as value added time. The times are expressed in seconds.

In the current state map the production lead-time is 2 days without including the procurement of raw materials. This lead-time accounts for non-value-added time. The monthly order request is a waste identified that can be alleviated through the implementation of virtual synchronisation of information presented in the future value map. Collaboration between supplier and manufacturer needs to be established to enhance production scheduling and reduce inventory holding. Other operations that need improvement are related to AM build and quality control (highlighted in orange in the current VSM). These operations are directly affected by the raw material quality and can delay the delivery. These operations are of paramount importance due to the limitations (porosity, residual stress, cracks and balling effect) found in metal AM production [12].

The critical step in the process for AM build is the setting of parameters for SLM production. The significant impediments are found in the material supply and the cost related to post-processing. The material supply takes about 4-6 weeks due to customs and regulations in the country. From the future map (value-adding activities highlighted in green), with the integration of virtual synchronisation, the AM build uptime has increased to 92%, while the implementation of automated testing has increased the uptime to 93%. Thus, the production is more organised, which consequently reduces the production lead-time to 1.82 days.

Although the VSM is a useful tool that clearly shows the process characteristics and lead-time, it does not show decision moments or the source of quality variations. Hence, a process flowchart, as dictated by lean thinking, is the next step presented in Fig. 5.

The flowchart shows that resource efficiency is a result of supplier selection. The manufacturer cannot rely on one supplier. They have to make provision for at least two reliable suppliers. The fact that the suppliers are overseas suggests that the lead-times can vary and that there is inventory holding.

As the synchronisation of the operations related to raw material procurement, manufacturing, and distribution is essential for integrated value creation, there is a need for the implementation of lean thinking to eliminate the cost of overruns and the excessive inventory of powders. The lean thinking developed for company A shows that it needs to improve the information sharing flow with their suppliers to reduce inventory storage and increase the quality of their final products. Company A might also consider strategic collaboration with leading organisations in the country to expand the SC network, improve the service, and flow of products and information. Such an approach could expand the adoption of AM and encourage value creation through the SC networks.

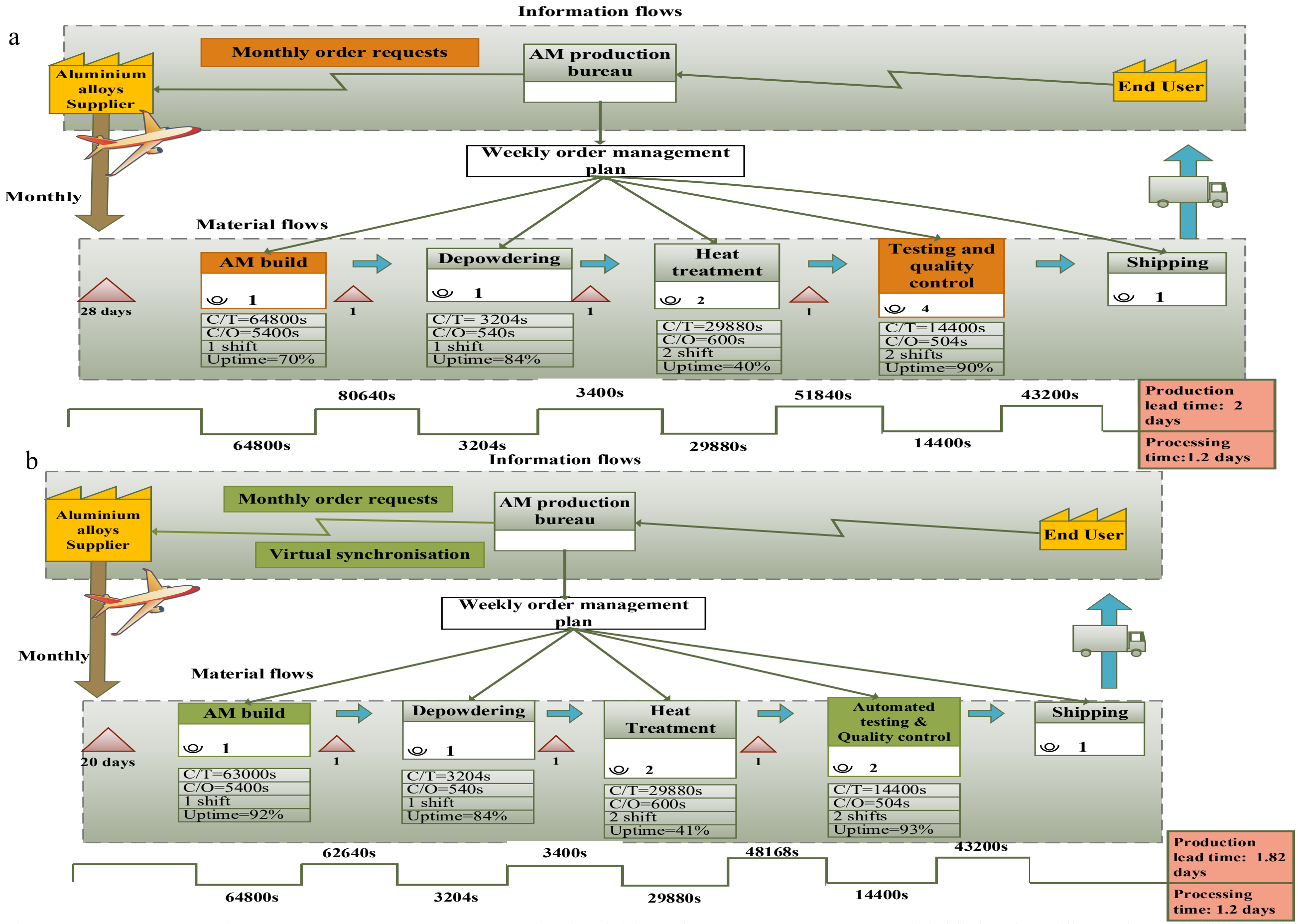

Fig.4. (a) Current state value map (orange: represents waste related activities); (b) Future state map (green: highlights the adding-value activities and the improved ones).

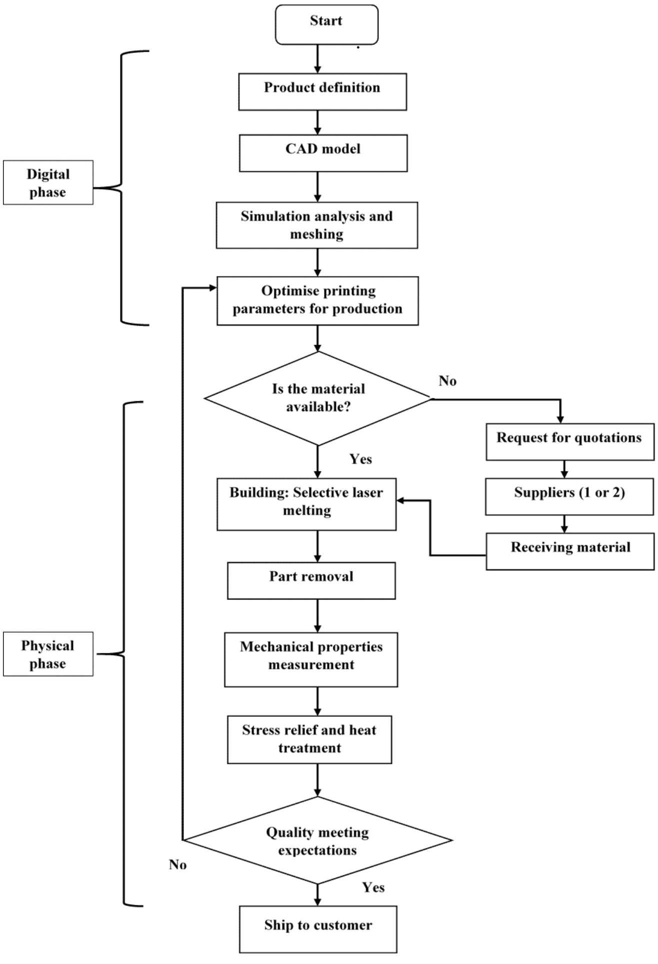

Fig. 2. Process flowchart for AM.

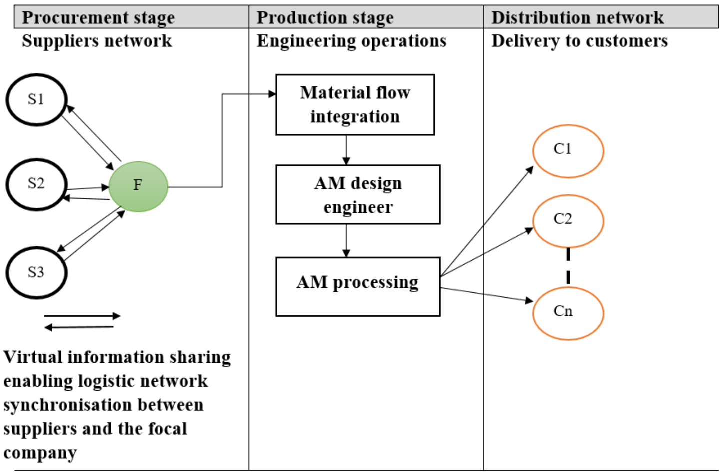

Fig. 6. Proposed framework for the integrated value-addition.

The proposed framework (Fig.6) involves the integration of different suppliers (S1, S2, and S3) that can be from different locations to ensure optimal transportation costs and lead-times for raw materials. The focal enterprise (F) should then integrate a virtual synchronisation of information sharing for tracking orders and avoiding supplier errors, unreliable delivery times, and high inventory costs. To ensure timely responses to different customer (C1, C2 …Cn) demands.

5. Conclusion and recommendations

The study focused on the integration of value-added activity in SC for metal component production using lean manufacturing tools, VSM and flowchart. The case study used pointed out the need to include the synchronisation of information along the SC networks as a value-added activity. Moreover, the VSM revealed waste that affected the production lead times and the cycle times. There is a significant amount of time spent (4-6 weeks) on the procurement of raw materials, and that includes transportation, inventory costs, and long lead times. This consequently hampered the increase in productivity for company A. One of the causes found is lack of partnership creation. This lack also resulted in improper production scheduling, thus increasing production time. The proposed framework suggests the need to involve different suppliers at the procurement stage to reduce uptime and production lead-times. It also suggests a virtual information network across the SC players to ensure a smooth flow of information and materials. In light of this, this study acts as a guide for operation managers and decision-makers in the adoption of AM for economic and operational benefits.

Some of the recommendations are as follows:

- There should be localised production and supply of AM metal powders for reduced SC complexity.
- Implementing more automated post-processing strategies that will reduce the time and cost associated with the production
- Consideration can be made for inter-organisational collaboration to create more values.

For future work, a structure of suppliers' network nodes and a cost analysis can be developed.

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