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I cast the drains down in Africa: AM-augmented casting as an enabler for the African manufacturing industry

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ABSTRACT: Africa's manufacturing sector is pivotal for economic growth and technological advancement. However, challenges such as inadequate infrastructure, supply chain disruptions, geopolitical tensions, and high costs hinder its development. These issues impede domestic production and reduce global competitiveness. Addressing them is essential for economic resilience. While beneficial, traditional strategies often overlook fundamental production constraints, especially in manufacturing sectors reliant on repair, maintenance, specialized components, and tooling. Manufacturing methods like casting face limitations in flexibility, cost, precision, and lead times. This research proposes using additive manufacturing (AM)-assisted casting to address these challenges. We identify agriculture and automotive as sectors with high potential to implement AM-assisted casting.

KEYWORDS: additive manufacturing, case study, design for additive manufacturing (DfAM), product lifecycle management (PLM)

1. Introduction

Manufacturing is experiencing rapid growth globally, propelling innovation, boosting productivity, and shaping the global competitive landscape (Dobbs et al., 2012). This sector is crucial for any country of region's economic growth as it contributes to gross domestic product (GDP), employment, living conditions, education, and a variety of other factors (B. Wang, 2018). Moreover, the health of the manufacturing sector is closely tied to the health of the national supply chain (Brun et al., 2020).

The future of manufacturing supported is by technologies in Industry 4.0 and 5.0. While regions such as North America, Europe, and Asia are keeping pace with emerging technologies (Klaus, 2016), continents like Africa lag behind in adoption due to issues with reliable and stable electricity, high-capacity telecommunication technologies, a shortage of domestic suppliers, high costs of importing and exporting goods, and outdated physical infrastructure and equipment (Kuteyi & Winkler, 2022). There is immense potential for African economies to directly adopt these technologies, eliminating the need to invest heavily in the maintenance of older infrastructure (Ayode, 2019). With the rapid developments of these digital technologies (Ndemo & Weiss, 2017) there is potential for African economies to ahieve maximum growth and development (Nemecková, 2021).

Manufacturing and supply chain (SC) intersect to facilitate the production and movement of materials, products and machinery. Together, these sectors create a ripple effect across many adjacent sectors such as agriculture, automotive, mining, and digital technologies (Ansu et al., 2016). Therefore, identifying the critical issues that contribute to manufacturing and SC inefficiencies should be of tantamount importance. Ndung'u et al. (2022) identified key barriers to Africa's manufacturing growth, including weak power infrastructure, inadequate transportation systems, restrictive bureaucracy, corruption, skills shortage, and obsolete traditional manufacturing (TM) techniques and machineries.

This paper investigates the integration of emerging technologies like additive manufacturing with traditional methods like investment and sand casting (Sama et al., 2018; Voigt & Manogharan, 2018) to streamline production, reduce dependency on external suppliers, localize manufacturing, and enhance material utilization - all objectives of vital important in the African context. Remarkably, metal casting plays a role in 90% of all manufactured goods and is a $33 billion industry in the U.S (Margolis et al., 1999). Almost 70% of metal castings are produced using the sand-casting process (Lynch et al., 2020).
To that end, the remainder of this paper is organized as follows. First, Section 2 reviews the global state of the manufacturing, discusses manufacturing and SC in the African context, and reviews the intersection of casting and additive manufacturing technology. Next, Section 3 describes the manufacturing economy and SC in primary African regions. Section 4 makes the case for the extensive use of AM-augmented casting approaches through AM hubs, and Section 5 concludes the paper.

2. Background

Modern SC face increasing challenges from global disruptions, highlighting the need for innovative solutions. This section examines the current state of manufacturing, Africa's role in global SC, and the potential of AM and casting to enhance resilience and efficiency.

2.1. Resilience challenges in modern supply chains and manufacturing

SC is an interlinked network of actors that includes producers, processors, manufacturers, distributors, warehousers, sellers, resellers, and the final consumer (Subramani et al., 2022). It entails everything from the purchase of raw materials, processing, transforming into valuable products, packaging, distribution, and storage before shipping off to the final consumer (Osei & Asante-Darko, 2022). The aftermath of the COVID-19 pandemic combined with increasing geopolitical tension across the globe is making the SC network more vulnerable and volatile. For instance, Russia's invasion of Ukraine resulted in hikes to oil and gas prices and the disruption of key trade routes (Bednarski et al., 2023). Subsequently, parts suppliers, raw material supplies and prices in the automotive industry were greatly affected, with the share prices of many automakers dropping as a result (Silberg, 2022). Beyond traditional conflicts, trade wars can also cause significant global impacts (Schindler et al., 2024; Zhao, 2023). Weather-related disasters such as flooding, hurricane, wildfires and drought can also impact the stability of SC (Burgman et al., 2023; Tchonkouang et al., 2024).

2.2. The impact of manufacturing and supply chain on African economies

The pandemic crippled many African countries, revealing their heavy reliance on exported goods as well as poor manufacturing conditions (Enoch, 2023). Many manufacturing industries in Africa use older manufacturing equipment and processes which makes it difficult to adapt to changing SC needs and volatility (Nachum, 2023). In global SC, Africa's key role is often the production and supply of raw materials. The continent boasts a vast reserve of critical minerals like aluminum, copper, iron ore, lithium, and manganese (Boafo et al., 2024) which are essential for the energy transition (Sterl & Shirley, 2024) as well as a wide variety of consumer products (Boafo et al., 2024). This highlights a substantial opportunity for the continent to help manufacturers and distributors simplify SC and decrease transportation costs by locally processing the metals into products. This is especially true for relatively low-technology products. However, the continent contributes only 2% of the world's manufacturing output, a decline from slightly more than 3% in the 1970s (Yeboua, 2024). Nearly all African countries have a Manufacturing Environment Index (which indicates the general preparedness of the manufacturing ecosystem) that is below the global average (Rägo et al., 2015). The region's growing abundant resource and current state necessitate strategic industrial adaptation (Ndung'u et al., 2022) capable of responding to sudden SC changes and demands.

2.3. Additive manufacturing and casting

Additive manufacturing (AM) involves manufacturing a part by depositing material layer-by-layer until a desired shape is achieved, enabling benefits can be challenging to achieve through TM processes and techniques (Javaid et al., 2021). Moreover, AM leaves a strong digital footprint that can drive a variety of machine learning process and integrated directly with quality assurance and control (Arul Prakash et al., 2020; Baldwin et al., 2024; J. Chen, Khrenov, et al., 2024; J. Chen, Pierce, et al., 2024; J. Chen, Xu, et al., 2024; Q. Wang et al., 2023). AM also presents opportunities for sustainability (Calignano & Mercurio, 2023). DebRoy et al. (2018) demonstrated that precise material deposition and reduced post-processing in metal AM can significantly cut energy consumption and lower emissions. The current paper focuses on the combination of AM with casting, which can often take two forms: 3D Sand Printing (3DSP) and AM-assisted Investment Casting (IC).

2.3.1. 3D sand printing

In 3DSP, the sand mold itself is directly printed. Recent research has shown that 3DSP allows for an increase in casting complexity, casting quality and weight reduction of finished parts, ensuring shorter manufacturing lead time, minimal product and development delays (Donaldson, 2018). The traditional sand-casting process requires a custom-built pattern and core boxes which may take weeks to months to manufacture. After patterns are manufactured, sand molds can be made in the range of minutes to seconds depending on the level of automation within a foundry. In contrast, 3DSP does not require the production of hard tooling (i.e. pattern, mold and core box). Instead, each individual printed mold is printed in sections, cleaned, and assembled. This process often takes hours to complete (Shah et al., 2022), but allows for every casting to be tailored. Figure 1 shows how sand printers utilize binder jetting technology to deposit binder resin onto catalyst-infused sand using an inkjet process (Walker et al., 2018). After each layer is printed, a fresh layer of sand is re-coated over previous layers, and this process repeats until the mold or cores are fully formed (Li, 2021). The more complex the tooling that is needed for the job, the longer and costlier the pattern making stage will be. This is the window of opportunity for printed molds which offer a faster way to print and assemble molds and cores.

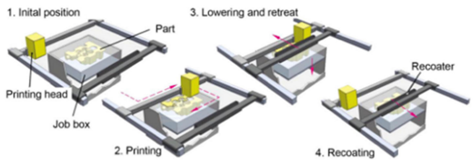

Figure 1. 3D printing mold process for sand casting (Li, 2021)

2.3.2. AM-assisted investment casting

AM-assisted IC involves 3D printing a wax investment pattern that can then be covered in a ceramic shell for IC (Tewo et al., 2019). In contrast, traditional IC requires high tooling cost for producing the wax patterns, and long process cycle time (Cheah et al., 2005). AM-assisted IC therefore enables flexibility in the design of customized products, highly complex geometries, process cycle time reduction, quality pattern and cast materials (Shah et al., 2023). Figure 2 shows the traditional IC process, which begins with pattern design and wax injection into a die (J. Wang et al., 2019). Next, wax patterns are assembled onto a wax sprue to form a cluster, then repeatedly coated in a ceramic slurry to build the shell (Pattnaik et al., 2012). After dewaxing through heating, molten metal is poured into the shell, cooled and allowed to solidify (Pattnaik et al., 2012; J. Wang et al., 2019). Finally, the shell is broken off, and individual castings are separated for post-processing. Although this process does not require expensive and elaborate tooling, it is still considered a costly process due to the high manual labor involved in preparing the wax pattern and slurry (Pattnaik et al., 2012). AM-assisted IC therefore provides cost-effective means of designing complex patterns, decreasing defects and improving its suitability for small batch production (Shah et al., 2022; Thymianidis et al., 2013)

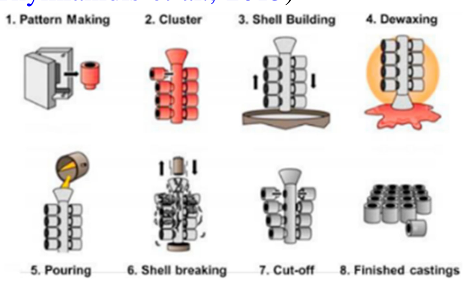

Figure 2. Schematic of IC process (J. Wang et al., 2019)

3. Regional differences across the continent

As Africa becomes increasingly vital to the global supply chain, addressing constraints in its manufacturing and logistics infrastructure is crucial. The rest of this section discusses important regional differences and commonalities across the continent.

3.1. East African region

East Africa, a region consisting of 18 countries, is bordered with the Sahara Desert to the north, the Indian Ocean to the east, and the southern and central regions of Africa to its west and south. It is the fastest growing region of the continent with GDP increases of 1.5% in 2023, 5.1% in 2024, and a projected increase of 5.7% in 2025 (AfDB, 2024). This growth is largely centralized to the Rwandan, Kenyan, Tanzanian, Ethiopian, and Ugandan economies, and most prominent in sectors such as transportation and logistics, manufacturing, technology and innovation, and urban development (AfDB, 2023). In addition to abundant natural resources, each state has established Special Economic Zones (SEZs) to incentivize investment and industrialization (Diop et al., 2012; Otiende & Niskanen, 2021). Significant manufacturing outputs include agro-processing, textiles, clothing, and leather. The transportation and logistics sectors in this region are improving significantly through e-mobility initiatives, enhanced public transport, digital integration, and upgraded air and road infrastructure. This progress is facilitated by strategic ports along the Northern Corridor (Port Mombasa, Kenya) and Central Corridor (Port Dar es Salaam, Tanzania) connecting landlocked nations.

3.2. North African region

North African consists of 7 countries (Algeria, Morocco, Tunisia, Sudan, Egypt, Libya and Western Sahara) and is positioned strategically between the Mediterranean Sea and Sahara Desert, with access to European and Middle Eastern markets. The region generates one third of the continent's total GDP, with the manufacturing sector contributing 18% to that share (Yeboua, 2024), making it the continent's largest and most industrialized region. Primary industries of the region include textiles, automotive, and food production. North Africa dominates the African automobile manufacturing market. The top players in this region are Morocco, Algeria, Tunisia and Egypt, with Morocco recently toppling South Africa as the leading car manufacturer in Africa. Interestingly, Morocco is fast becoming a prime supplier of European manufacturers' components such as seat kits, and wiring harnesses, particular for car interiors (Smith, 2020). This reveals the region's high manufacturing potential in automobile manufacturing especially with OEMs (Original Equipment Manufacturers) like Volkswagen, Renault-Nissan, Toyota, Mercedes-Benz and Toyota investing heavily in the region.

3.3. West African region

West African, consisting of 16 countries, sits between North Africa, the Sahara Desert, and the Atlantic Ocean. Important economies in the region include Ghana, Ivory Coast, Nigeria, and Senegal (Adegbite, 2021; Semanou, 2022). Major manufacturing sectors include fuels, food and beverages, textiles, and apparel, with the region being the sixth-largest cotton manufacturer globally. Nigeria, the continent's leading oil and gas producer, significantly influences regional trade and manufacturing activities as Africa's fourth-largest economy (Adegbite, 2021; Dobbs et al., 2012). The region's connectivity is supported by active ports, road networks, and air routes, mainly trading with the European Union.

3.4. Southern Africa region

Southern Africa includes Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Eswatini (formerly Swaziland), Zambia, and Zimbabwe. The region's coastline stretches from the desert border with Namibia with the Indian ocean in the east and the Atlantic Ocean to its west. Primary industries include textiles and clothing, automotive manufacturing, metals, chemicals, plastics, and wood products. South Africa, the continent's largest economy, is a prominent manufacturing hub, especially in the automotive, iron/steel sectors (South African Government, 2017).Mining significantly contributes to the economy, exporting mainly gold, platinum, cars, and diamonds, supported by extensive trade partnerships with global powers such as China, US, EU, Germany, India, and Japan.

3.5. Commonalities

Across all regions, the agriculture/agro-processing and automotive sectors emerged as critical sectors for potential high-impact growth. These two sectors have also been identified African Continental Free Trade Area (AFCTA) in strategic plans for priority development in the continent (Signé & Munyati, 2024). Transportation, logistics, and pharmaceutical industries were also identified as key development areas. Agricultural and agro processing contributes approximately 35% to Africa's GDP and significantly exceeds the global average in economic contribution (Munyati & Signé, 2023). Moreover, 70% of Africa's population rely on agriculture as their primary source of livelihood, making agriculture the backbone of its economy (Woldemichael et al., 2017). Undeniably, agriculture and agro-processing sector has great potential to spur economic growth and create sustainable employment through forward and backward linkages (Thindisa, 2022). Investment and restructuring of this sector's infrastructure is therefore crucial for productivity and economic growth (Gajigo & Lukoma, 2011). Likewise, the automotive industry has also rapidly expanded, positioning Africa as an emerging global automotive hub. AfCFTA's strategy involves scaling production to 4–5 million vehicles by 2035, emphasizing electric vehicle (EV) production and sustainable farming technologies (Signé & Munyati, 2024). This expansion includes significant investments in assembly, maintenance, and component production (Agarwal et al., 2022).

4. Proposed direction and approach

AM-augmented casting (both 3DSP or AM-assisted IC) can positively change the manufacturing on the continent. This is especially true in the sectors identified above because their equipment and machinery require complex geometry (Shah et al., 2022) during production. Industrial adaptation of AM-augmented casting to the agriculture and automotive sectors could well be a viable approach to promoting manufacturing output and SC efficiency. The approach offers the benefit of facilitating lead time and cost reduction, design flexibility, and part quality improvement by enabling precise control over pattern geometry and surface finish (Shah et al., 2023).This also provides a practical solution to achieving remanufacturing and reverse logistics for supporting the prevailing TM firms, including high-value parts in African sectors (Strong et al., 2020). This section proposes a framework to improve the manufacturing and SC issues of the selected industries using AM-augmented casting. Based on evidence and trends identified from our extensive research, we believe this adoption should start with the agriculture/agro-processing industry and then the automotive industry.

4.1. Applications of AM-augmented casting in Africa

AM allows for the rapid creation of prototypes, enabling faster design iterations and reducing wait times. In the automotive industry, production of custom tools, jigs, suspension components, fixtures, structural parts, and engine components can be produced faster and with more flexible design iteration using AM-augmented casting. Traditionally, sandcasting is usually used to produce engine blocks, an important component in the automotive industry. The engine block is the largest and main casting part in engine parts which produces space for cylinders, allows passage of coolant, exhaust, and in-take gases over the engine, and houses the crankcase and camshafts (Li, 2021). Integration of AM with sand casting in this part of the automotive industry provides the benefit of improving the quality of engine blocks by allowing better cooling channel design, more complex geometries, and reduced defects. A key example is Volkswagen leveraging AM to manufacture complex vehicles structures (V., 2021). Notably, South Africa has been at the forefront of using AM-augmented casting to produce high quality commercialized complex components like hydraulic press for the automotive industry (Gao et al., 2022). Similarly, AM-augmented casting benefits the agricultural and agro-processing industry by enhancing the production of agricultural machineries, parts and planting facilities (Bourell et al., 2017). Applications include gear boxes and engine components for tractors, harvesters and threshers for harvesting, plows and rototiller tines for soil cultivation, and pumps and valve parts for irrigation systems. Additionally, South Africa's agro-processing sector has demonstrated AM-augmented casting's potential in producing high-quality, customized components for food processing/packaging machinery, improving productivity and efficiency (International Trade Administration Commission of South Africa, 2016). AM-augmented casting extends to smart agriculture, enabling integration of AI and IoT (Lu et al., 2024). Notably, Liu et al. (2018), built a flexible grasping claw module, integrating it with a robotic arm for automated fruits and vegetables handling using machine vision and grasp control. These applications showcase the vast potential for African Manufacturers to compete globally. Sustained investment in research, innovation and infrastructure is essential to realize the full benefits of AM-augmented casting in Africa.

4.2. Strategic approaches for AM-augmented casting adoption in Africa

It is envisioned that once the foundries receive their casting order and decide on their manufacturing mode, they order the IC or sand molds and cores from AM hubs as shown in Figure 3. The figure is inspired by the hybrid metal-AM SC in US diagram in (Strong et al., 2019), showing how AM-augmented casting integrated SC factors in the costs for potential part failure or scrap. Traditional manufacturers receive low-production-run orders from customers and send CAD models to an AM hub. The hub produces near-net metal parts and ships them to heat treatment facilities. Upon treatment, parts are sent to traditional manufacturers for hybrid post-processing before final delivery to customers using existing methods. The strategic placement of AM hubs across African regions, in specific countries like South Africa, Nigeria and Ethiopia is based on their economic attractiveness such as existing industrial infrastructure like foundries, proximity to raw materials, skilled labor and local market demand. Beyond these economic considerations, AM-augmented casting regional hubs adoption also drive sustainability (Calignano & Mercurio, 2023). Attaran (2017) emphasized that in regions where reliance on complex imported tool poses logistical and financial challenges, localized manufacturing with AM-augmented casting can reduce cost while shortening SC and cutting transportation related emissions.

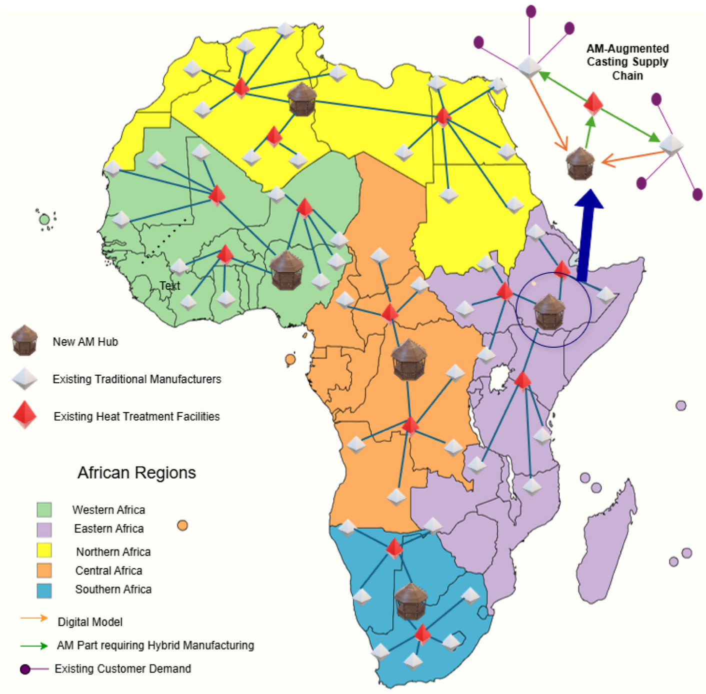

Figure 3. AM-augmented casting supply chain with AM regional hubs

Hub locations are the main drivers for the allocation decisions. Alumur & Kara (2008) discussed a review of several hub location and allocation problems such as hub with fixed cost, hub centering, and hub covering using both single and multiple allocations. Campbell et al. (2018) presented a survey on hub location literature where they discuss the evolution of the hub location problem (HLP), evaluating from the origin to its current state. Daskin & Dean (2004) discussed the importance of facility location models where poorly located facilities or too many or too few facilities will increase expenses and diminish customer service. According to L. Chen et al. (2014), optimally located sites can improve operational performance and help gain competitive advantages in both the short term and long term. Moreover, the location of facilities with respect to their competitors as well as customers has a significant impact on a firm's ability to run and deliver efficiently (Daskin, 2013).

Over time, several research works have highlighted the need and the advantages of integrating AM and machining processes (Hur et al., 2002; Xiong et al., 2009). Such hybrid strategies have been developed for the environment where additive and subtractive operations are repeated in a cycle until the final part is created (Karunakaran et al., 2010; Xiong et al., 2009). Others contend that hybrid manufacturing has the potential to improve the capabilities of TM by integrating AM where traditional machining would post-process the AM metal parts (Strong et al., 2017). Other researchers recognize that existing manufacturers with heterogeneous bills-of-material may develop AM capabilities to isolate disruptive, low-volume production from scalable mass production (Sasson & Johnson, 2016).

5. Conclusion

This paper advocates for the strategic research, development, and implementation of AM-augmented casting as a transformative technology for the African manufacturing sector. By bridging conventional sand-casting and IC methods with modern AM capabilities, this hybrid approach offers a pathway to enhance production efficiency, reduce costs, and improve the flexibility of manufacturing processes. The integration of AM into TM can enable Africa to localize production, reduce reliance on imported goods, and address challenges in SC resilience. These advancements could catalyze broader industrial development and support the continent's transition toward Industry 4.0. However, to effectively leverage AM-augmented casting, the establishment of regional hybrid manufacturing hubs is essential to integrate AM-augmented casting with the existing SC. This localized approach accounts for specific economic, cultural, and infrastructural conditions in the sectors and the regions to maximize the impact of this technology.

To further this initiative, targeted design-based case studies of the AM hubs are recommended to validate the feasibility, workflow, and economic potential of AM-augmented casting in specific industries and regions. These studies can provide actionable insights for stakeholders and policymakers, enabling tailored strategies that align with local contexts. Additionally, partnerships between governments, academia, and industry will be crucial in building the necessary infrastructure, technical expertise, and SC networks to support this transition.

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