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Blockchain-empowered Distributed Additive Manufacturing-as-a-Service: An Architectural Perspective

Sergio Salinas Monroy, Pan Li, Yuguang Fang, and Kenneth A. Loparo

Abstract—Additive Manufacturing (AM) is transforming the way that we fabricate, deliver, and consume a wide range of products and components, including those for consumers, medical devices, automobiles, and aircraft. In AM, 3D-printers are used to fabricate products by depositing material in a layer-by-layer fashion, leading to extremely low marginal production costs and significantly simplifying the manufacturing supply chain by providing the opportunity for production that is much closer to consumers. With extremely low marginal costs, AM facilities can quickly scale their production up and down, or redirect their resources to produce entirely different types of goods to meet dynamic market demands. However, most AM companies that employ 3D-printers have not yet upgraded their operations in a way that improves their supply chain. In this paper, we first offer an overview on the state-of-the-art of AM supply chains and then present a novel blockchain-empowered system architecture, namely, Additive Manufacturing-as-a Service (AMaaS), that can facilitate the speedy adoption of AM in manufacturing industries. Finally, we identify several major research challenges in terms of market design, control algorithms, and security, as well as research directions to tackle them.

Index Terms—Additive Manufacturing (AM), Supply Chain, Auction, Blockchain, Cyber-physical systems.

1 Introduction

Additive Manufacturing (AM) is transforming the way that we fabricate, deliver, and consume a wide range of objects, from consumer products, to medical devices, automobiles, and aircraft [?]. In AM, 3D-printers are used to build by depositing materials in a layer-by-layer fashion, allowing them to build a wide range of objects with complex geometries and varying levels of material properties (e.g., tensile strength, heat transfer, etc.). Due to this remarkable ability, manufacturing companies and governments are rapidly incorporating AM into their manufacturing processes [?].

AM is superior to traditional manufacturing methods, such as subtractive and forging processes, in many ways. 3D-printers can build complex products with fewer parts, thus drastically simplifying assembly and reducing the production costs. Because 3D-printers offer extremely low marginal costs, AM facilities can quickly scale their production up and down, or redirect their resources to produce entirely different types of goods without losing profitability. For these reasons, AM can democratize manufacturing by enabling small enterprises to enter the market with low capital investments, e.g., only a few 3D-printers and low production volumes are needed to become profitable [?]. Many such small-scale AM facilities have already emerged in the US and around the world [?].

Although many companies have already adopted AM to build their products, the vast majority of these efforts focus on simply replacing traditional manufacturing processes (e.g. conventional machining operations) with 3D-printers, missing the opportunity to simplify their supply chains. In particular, traditional manufacturing relies on a few large manufacturing facilities that are usually far away from customers, and hence needs long lead times and large production orders to be profitable. In contrast, by enabling many smaller facilities to control their production resources in real-time, AM can build customized products on-demand closer to the customers, shortening the shipping distances. Besides, such enterprises can be made mobile, e.g., 3D-printing on wheels (i.e., trucks) [?], which can be brought much closer to where the products are needed, adding another dimension for optimizing the AM supply chain.

To facilitate the adoption of AM in a way that enterprises can fully take advantage of its benefits, we propose a new blockchain-empowered system architecture for *Additive-Manufacturing-as-a-Service*, or *AMaaS*. We consider an AMaaS where small AM enterprises, called *micro-manufacturers*, can adaptively pool their 3D-printing resources together and offer customized services on an on-demand and pay-per-use basis. By aggregating their manufacturing resources, micro-manufacturers can fulfill large orders that no single micro-manufacturer could have completed on its own, and customers, e.g., companies who sell final products to consumers, or consumers themselves, can access the resources from multiple micro-manufacturers, possibly mobile, without having to deal with each of them individually. Moreover, by jointly managing the production resources of the micro-manufacturers by means of real-time control processes, micro-manufacturers are able to reduce shipping costs by allocating production orders to the nearest available micro-manufacturers, and quickly scaling up the overall production to meet the dynamic and diverse object demand for products.

However, there are several challenges that need to be addressed before the benefits of AMaaS can be fully reaped. First, we need a system architecture that realistically cap-

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tures not only the dynamics of supply chain and manufacturing but also the financial and data transactions between a large number of heterogeneous market participants, including raw material suppliers, logistics operators, micro-manufacturers, product designers, and IT service providers. Second, because the AMaaS jointly sells products to customers and controls the micro-manufacturer resources, it needs an effective mechanism to both determine the product prices and dispatch the 3D-printers in the systems, in such a way that resources are optimally used, micro-manufacturers make a good profit, and the product demands from buyers are met. Third, to ensure that the AMaaS platform operates in real-time and is trusted by all participants, the AMaaS needs a tailored blockchain that can effectively process transactions and facilitates audits by the market participants.

In this paper, we first overview the state-of-the-art of AM supply chain systems, thus providing an extensive review of the potential use cases of AMaaS. Then, we introduce our blockchain-empowered distributed AM architecture that can facilitate secure and efficient implementation of AMaaS. Finally, we present several open research challenges and discuss possible solutions for AMaaS.

2 Related Works

In this section, we review the state-of-the-art in AM supply chains, control approaches, market mechanisms, and platforms.

2.1 Existing AM Supply Chain

There are currently several AM companies that offer partial AMaaS services through a centralized architecture such as FastRadius [?]. These companies often operate 3D-printing facilities at several different locations and some of them even allow third-party manufacturers to join their network. Unfortunately, their platforms offer limited opportunities to simplify the manufacturing supply chain. For example, they prevent buyers from automatically dividing large orders between multiple AM facilities without having to individually contract with each facility. They also make order assignments without considering the manufacturing costs, capacity, and shipping distances in the overall system.

Meanwhile, several architectures have also been proposed for AM supply chains in the current literature, including vertically-integrated architectures [?] and cloud-control distributed architectures [?]. Previous works have found that having many smaller manufacturing facilities instead of only a large one offers lower operating costs and higher machine utilization. Moreover, some researchers propose novel architectures for different types of on-demand services, where a digital platform coordinates various types of physical resources from multiple independent operators to meet the demand from users, e.g., ride-sharing services such as Uber. Although their models take into account mobile resources, e.g., vehicles, their use of simplified physical models are inadequate for AMaaS systems, which have to deal with highly complex and unpredictable manufacturing and materials resource dynamics.

2.2 Existing Optimal Control of the AM Supply Chain

Several approaches have been proposed to manage the manufacturing resources of AM supply chains in a way that optimizes certain objectives. These efforts mainly focus on finding an allocation of machines to process orders to minimize the makespan either in a one-shot scenario [?] or in a long-term time average scenario [?].

Many algorithms have also been designed to find optimal placements of objects inside the work area of manufacturing facilities with multiple 3D-printers [?]. However, previous works only consider either one-shot scenarios that ignore the impact of current control decisions on future system states, or focus on a single manufacturing site, disregarding the shipping and transportation challenges in AM supply chains.

In our recent work [?], we have proposed an AMaaS optimal control system that considers a long-term average. The control system optimally allocates 3D-printers from a set of geographically distributed micro-manufacturers to buyers' production orders.

2.3 Existing Market Mechanisms for AM supply chains

Similar to other cyber-physical systems, AMaaS systems need to find an effective way to determine the price of its services to allow buyers to access manufacturing resources at low costs while guaranteeing that micro-manufacturers can make a good profit. Auctions have been successfully used to price and efficiently allocate scarce goods and services in various systems, such as cloud computing and power systems. However, existing mechanisms are unable to consider both the 3D-printers' limited capacity and buyers' sensitivity to location and quality of 3D-printers used to build their products.

Our work in [?] demonstrates that it is possible to design an auction mechanism that maximizes the profits of micro-manufacturers under the complex production capacity constraints of the AM supply chain by using deep learning-based auctions.

2.4 Existing Platforms for the AM Supply Chain

2.4.1 *Centralized platforms*

Currently, supply chains depend on centralized systems operated by multiple parties to collect data about the location and production status of the completed products. This results in low visibility for customers and manufacturers about the status of the products and fails to provide real-time monitoring and control [?]. Although a centralized data collection scheme could help solve this challenge, it would introduce a single-point-of-failure and suffer from poor scalability, which is critical to handle the large amount of potential products in AMaaS systems.

2.4.2 *Blockchains*

There exists a few works that apply the blockchain to AM supply chains, e.g., [?]. The blockchain can be used to store critical system data such as object designs, manufacturing machine characteristics, and raw material levels, while preserving its integrity and availability. The blockchain also allows companies to expedite paperwork by reducing

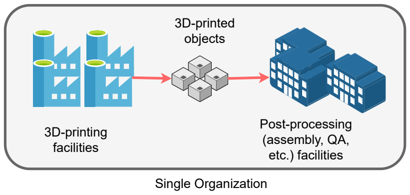

Fig. 1: AMaaS architecture for a single enterprise.

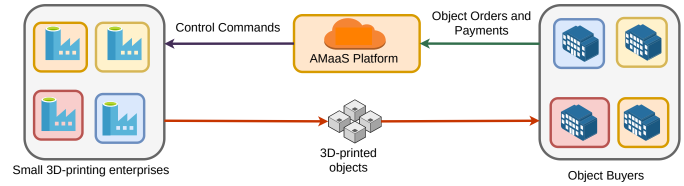

Fig. 2: AMaaS architecture for multiple micro-manufacturers.

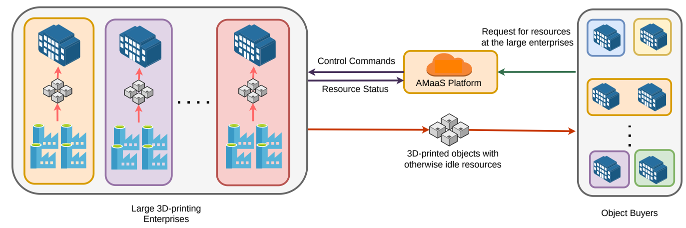

Fig. 3: AMaaS for idling resources of large enterprises.

the need of verifying the authenticity of physical paper documents [?]. Although such existing works simplify the management of the AM supply chain by using blockchain, they cannot account for the real-time requirements of the AMaaS, and hence are unable to optimize the manufacturing resources in an efficient and scalable way.

3 Possible AMaaS Configurations: Use Cases

In this section, we present several possible AMaaS use cases that show how AMaaS helps both existing and newly emerging (smaller) business enterprises to share their manufacturing resources to better meet the product demand.

3.1 Single-enterprise AMaaS

In a single-enterprise AMaaS model, a company owns all AM facilities and consumes the additively manufactured parts that it produces. Such enterprises usually include vertically-integrated companies who control the supply chain from beginning to end. This model is common in the aerospace and automotive industries. Fig. **??** illustrates the single-enterprise AMaaS architecture.

Because a single-enterprise AMaaS has access to all real-time status information from the AM facilities and the object market demand, it can discover a globally optimal solution to dispatch its manufacturing resources. Moreover, because the enterprise is to manufacture products for internal use, it can focus on minimizing its operating cost without having to set prices for the manufactured products.

3.2 Multiple Micro-Manufacturers AMaaS

Multiple independently-owned AM facilities, called *micro-manufacturers*, can pool their resources together and offer their services through a centralized AMaaS platform to buyers. By pooling their resources, micro-manufacturers can handle large production orders that they would otherwise not be able to handle. Moreover, buyers can conveniently access a vast amount of AM resources through a centralized platform. In this scenario, small enterprises can sell objects even with only a few 3D-printers. Due to low marginal costs, even if they build batches of small parts or even one-off parts, it is still profitable. We show this architecture in Fig. **??**.

The AMaaS platform creates a market that offers available 3D-printers from micro-manufacturers to buyers. Buyers' service requests and the corresponding payments are submitted to the AMaaS platform, which are then distributed in a privacy-preserving and secure manner to the corresponding micro-manufacturers.

3.3 AMaaS architecture for Idling Resources from Large Enterprises

Large AM companies can increase their resource utilization by offering their idling manufacturing resources to an AMaaS platform. The idle resources can be offered to buyers alongside dedicated resources. Because idle resources come online sporadically, buyers can take advantage of lower prices in exchange for reduced ability to plan their production ahead of time. Fig. **??** illustrates this architecture.

3.4 Auxiliary Manufacturing Services Through an AMaaS

Besides using 3D-printers to build products, buyers need access to additional services, such as product design bureaus, dedicated quality assurance facilities, and post-processing. Specifically, buyers first need a product design. They can purchase pre-made designs through vendors on an AMaaS platform, hire a design bureau to make a custom design, or simply use the design that they have already had. Moreover, buyers may need quality assurance services for their products either at a micro-manufacturer or at a third-party facility. The AMaaS enables additional small enterprises to offer their auxiliary services, and allows buyers to easily bundle heterogeneous services from multiple providers.

4 Our Proposed System Architecture

To unify the configurations described in Section **??**, we propose a system architecture that captures the complex cyber, physical, and financial interactions among AMaaS participants using a layered approach. Next, we describe the proposed architecture in more detail.

4.1 Physical Infrastructure Layer

The physical infrastructure layer includes both fixed and mobile AM facilities, namely, manufacturing equipment and the vehicles used to transport raw materials and products. This layer is responsible for transporting the raw material

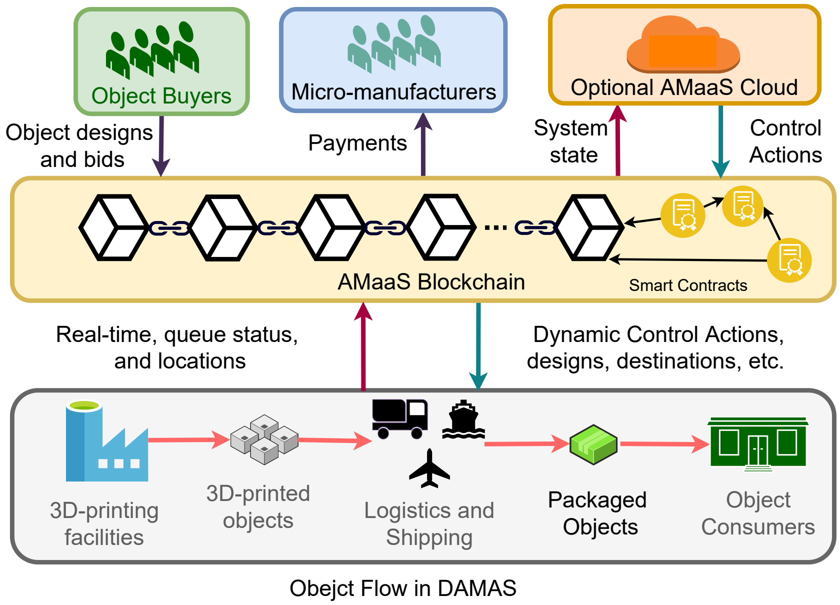

Fig. 4: The architecture of our AMaaS: a blockchain-empowered secure and economically-robust distributed AMaaS platform.

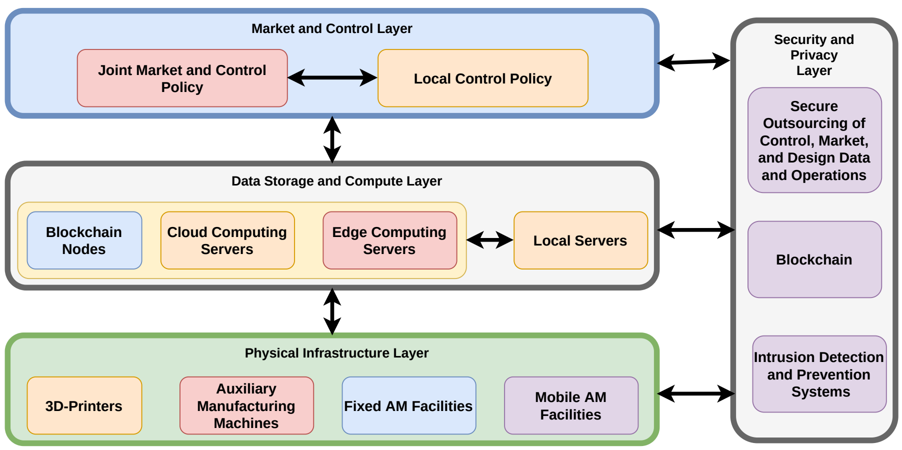

Fig. 5: Layered system architecture for AMaaS

from suppliers to the AM facilities that operate the 3D-printers to manufacture the objects and deliver the completed products to buyers. In addition, this layer contains the machines that provide post-processing and quality assurance inspection services.

4.1.1 3D-printers

3D-printers are the key devices of an AMaaS system. Their operations are described as follows. First, they receive the design files that describe the shape and properties of the products to be manufactured. Second, they build the products one batch at a time. During production, the 3D-printers report their status, such as printing progress and manufacturing errors. Once they start printing a batch of products, the 3D-printers must complete it before moving to new objects. If 3D-printers are idle, they report their capabilities to the AMaaS, including the size of their printing bed, available configurations, and printing capabilities.

4.1.2 Auxiliary Manufacturing Machines

Besides 3D-printers, the AMaaS uses several devices to perform post-processing and quality assurance of the completed products. Specifically, after 3D-printers build a product, manufacturers usually need to perform certain processes, such as smoothing of surfaces or removing support structures used during the printing phase. Once products are finalized, they are inspected to ensure that they are defect-free and meet the design requirements. The machines that perform post-processing and quality assurance report their status and capabilities to the AMaaS system. These machines may be co-located with the 3D-printers within the same AM facility or located at a dedicated facility at a different location.

4.1.3 AM Facilities

AM facilities are the buildings and vehicles that house the 3D-printers and the auxiliary manufacturing devices. They provide a physical space to store raw materials and manufactured products before shipping. The AM facilities measure and report their amount of raw materials available to produce objects and the physical space remaining to store newly-produced products. If the AM facility is mobile, it also reports its location.

AM facilities can be strategically placed to serve multiple regions, or they can be mobile. Mobile micro-manufacturers can drive their facilities to the shipping destination of the product and then produce it on the spot [?], [?]. Mobile micro-manufacturers can also be implemented inside temporary facilities, such as shipping containers, that can be easily transported to a new location to meet seasonal product demand.

4.2 Data Storage and Computing Layer

The data storage and computing layer is composed of a blockchain, the cloud, and edge servers.

4.2.1 Blockchain Nodes

The blockchain comprises blockchain nodes that maintain the distributed ledger and process transactions. These nodes can be operated by manufacturers, buyers, and product designers interested in maintaining the operations of the AMaaS system. They can also be operated by third-parties interested in obtaining the AMaaS cryptocurrency, called *morning-coin*, which can be exchanged for manufacturing services.

4.2.2 Cloud and Edge Servers

The cloud and edge servers provide computing and data storage resources to the AMaaS platform, buyers, and AM facilities. Buyers and design bureaus store their design files in the cloud to allow AM facilities to download them for production. In addition, design bureaus can join their own cloud or edge servers to achieve higher protection guarantees of their intellectual property.

The AMaaS platform uses the computing resources to determine the optimal market and control decisions. AM facilities can execute distributed control and market mechanisms on-site using edge computing. AM facilities are also positioned to aggregate their device data before transmitting it to other layers.

4.3 Market and Control Layer

The market and control layer orchestrates the overall operations of the AMaaS system. Its main objective is to assign production orders from buyers to AM facilities, set the prices for manufacturing services in such a way that the profit of the AM facilities is maximized, and let the buyers pay a fair price. To this end, the market and control layer jointly considers the status of the manufacturing resources and the demand for products to dispatch the manufacturing resources. This layer also records its results as transactions on the blockchain to facilitate trustworthy bookkeeping.

4.3.1 Local Control Sub-Layer

Although the market and control layer are able to determine the control decisions for all devices in the AMaaS system, a fully centralized control approach may become a bottleneck for large-scale AMaaS systems. To overcome this challenge, the AMaaS can delegate certain functions to the AM facilities that implement a local control sub-layer with the help of an edge server.

Some computationally intensive problems could be delegated to the AM facilities. For example, AM facilities could locally find the best packing of products on its 3D-printers and find optimal production schedules. We further explain this issue in Section **??**.

4.4 Security and Privacy Layer

The security of AM operations and the buyers' privacy are critical to the AMaaS. Sophisticated adversaries can infiltrate the devices of the AMaaS to steal sensitive business information, sabotage manufacturing operations, or inject defects into the manufactured products. To protect an AMaaS system, the security and privacy layer implements various mechanisms to monitor and protect the AMaaS operations and its data.

4.4.1 Blockchain

The AMaaS system should provide confidence to both micro-manufacturers and buyers. Buyers should be able to verify the integrity of the designs used to build their products and micro-manufacturers should be ensured that they will receive payment after producing products for various buyers.

To overcome this challenge, an AMaaS uses the blockchain, which allows both micro-manufacturers and buyers to independently verify the integrity of the design files and related documents. The blockchain can also be used to efficiently scale the manufacturing resource allocation by using a distributed implementation.

An AMaaS system maintains a blockchain to provide a secure record of the data transmitted between layers and support financial transactions among the AMaaS participants. Specifically, the devices in the physical infrastructure layer, e.g., 3D-printers, mobile AM facilities, etc., record their status data on the blockchain. AM facilities keep an up-to-date record of the products that have been manufactured.

To dispatch the AMaaS manufacturing resources, the market and control layer first obtains the data recorded by the physical infrastructure layer from the blockchain and then adds the results of its control and market algorithms as a new block in the existing blockchain.

Because the design files can be very large (e.g., more than 1 GB), buyers do not upload them directly to the blockchain. Instead, they store the hash of their files on the blockchain and upload their files to the cloud. The AM facilities can then access the files stored in the cloud and verify their integrity and authenticity using the hash values stored on the blockchain.

In terms of financial transactions, the AMaaS blockchain uses a cryptocurrency to support payments from buyers to AM facilities in exchange for products. Each AMaaS participant maintains a blockchain identity, e.g., a wallet, that they can use to distribute and receive cryptocurrencies.

The blockchain allows the use of smart contracts to support the complex market and control mechanisms implemented in the market and control layers.

4.4.2 Secure Outsourcing of Market, Control, and Design Data and Operations

This module is responsible for securely implementing data storage as well as market and control computations in the cloud and edge servers. Because the data of a buyer and an AM facility required to operate the AMaaS are sensitive, it needs to be kept secret from other AMaaS participants and third parties (e.g., edge and cloud servers, and design bureaus). To this end, this module allows the AMaaS system to operate with encrypted, obfuscated, or partial data and provide a way to verify the integrity of the computational results.

4.4.3 Intrusion Detection and Prevention System

The intrusion detection and prevention system module monitors network traffic, end-point protection system data, and sensor data from the physical devices to detect and mitigate cyber-attacks. To detect sophisticated adversaries, it is important that this module not only monitors the network data but also the data streams from heterogeneous sensors at the physical infrastructure layer that may reveal such attacks.

5 Research Challenges

The AMaaS system can significantly improve the AM supply chain, by allowing the broader public to access AM and enabling new small enterprises to successfully compete in the global manufacturing market. However, there are several research challenges that need to be addressed before it rolls out for commercialization. Next, we summarize the key research challenges in our AMaaS.

5.1 Economically Optimal Control of Our AMaaS System

One of the main challenges in our AMaaS is to find a joint market and control strategy that meets the complex physical constraints while maintains acceptable prices for buyers and ensures a profit for manufacturers.

Designing such a market and control mechanism is particularly challenging due to the fact that product pricing depends on the availability of manufacturing resources at the micro-manufacturers, which in turn depends on the dispatch actions of the AMaaS. In other words, simply maximizing the number of products that the AMaaS builds for the buyers by dispatching the maximum number of 3D-printers could risk committing too much resource to produce products at higher prices in the future, resulting in lower profits for the micro-manufacturers. Therefore, the AMaaS should be able to optimally set prices and dispatch the manufacturing resources while balancing both the physical and the financial objectives.

Moreover, because the market outcome determines the amount of requested physical manufacturing resources to be dispatched by the AMaaS, the market needs to be regulated with an appropriate control mechanism. Specifically, the market design needs to ensure that the available manufacturing capacity can produce the product sold to the buyers. It also needs to ensure that the AM facilities have enough raw materials to produce the requested products, and enough physical space to store them. The products should also be produced by AM facilities close to the buyers to ensure that it can meet delivery deadlines, reduce transportation costs, and simplify the AM supply chain.

5.2 Secure and privacy-preserving operation of the AMaaS

Sophisticated adversaries can launch attacks that aim to sabotage the operation of the AMaaS or steal private information from customers and manufacturers. We identify the following two research tasks in this area.

5.2.1 Market and Control Mechanisms That Are Resilient to Cyber-attacks

Besides efficiently operating the AMaaS system, the market and control mechanisms should be able to operate effectively when they are under a cyber-attack. Sophisticated cyber adversaries aiming to sabotage the operations of the AMaaS system can launch several types of attacks, which should be addressed effectively.

In particular, attackers can manipulate the sensor data to change the outcome of the market mechanism, which can result in infeasible control decisions, unfair financial gains for the attacker, or delay of the production of buyers' products. Besides sensor data, the adversaries may attempt to manipulate the product design at the AM facilities after they have been downloaded from the cloud and verified with the help of data on the blockchain. Modified files can introduce defect into the products and can also cause damage to the 3D-printers.

Attackers may also pose as buyers to submit malicious product production requests. Malicious requests that reserve large amounts of printing bed area can be used to launch denial of service attacks to prevent legitimate users from accessing the manufacturing resources. Under dynamic pricing schemes, carefully crafted requests may also unfairly influence the prices of products. Therefore, there is a dire need to investigate how such attacks are launched and develop corresponding strategies to mitigate them.

5.2.2 Secure and Privacy-preserving Outsourcing of the Market and Control Mechanisms of the AMaaS

For buyers and AM facilities to trust our AMaaS system, their sensitive data used for market and control operations should be kept secure and private in order to protect their intellectual property. To this end, we need to develop effective strategies to allow the AMaaS participants to protect their private data before uploading it to the blockchain or the cloud while keeping the AMaaS system in normal operation using only the protected data. The sensitive data can be protected through encryption and obfuscation or by distributing the sensitive data among multiple servers, e.g., with secret sharing mechanisms.

The outsourcing approaches need to consider the heterogeneous data streams in the AMaaS (e.g., sensor data, product designs, market data, etc.) and allow different levels of privacy control that buyers and AM facilities desire.

5.3 Optimal Manufacturing Facility Placement

Because shorter shipping distances are a key advantage for our AMaaS, the placement of fixed AM facilities is a key design option. The ideal location for an AM facility depends on the number of current and future potential object buyers in the area, demand patterns, expected economic growth, etc. However, because these variables are hard to predict, finding a location to maximize a firm's profit is a challenging task, especially for small businesses. Moreover, the addition of mobile AM facilities to the AMaaS system can assist with dynamic demand patterns both in time and space. Hence, there is a need to develop methods to determine the minimum amount of AM facilities to be used and their locations to meet the potential demand.

5.4 Object Placement on Printing Beds.

After a production order is assigned to an AM facility, it needs to find an arrangement of the products on the printing beds. This arrangement needs to ensure that the products do not overlap and that they all fully fit within the printing bed dimensions. This problem can be modeled as a bin-packing problem and is highly-complex due to the large solution space. There is a need to develop both efficient solution algorithms to solve the object placement problem and outsourcing algorithms that can manage the communications with the edge servers that will implement them. The solution must go beyond finding local solutions and integrate the packing of objects at a single facility to the system-wide control decisions.

6 Conclusions

In this paper, we have discussed the state-of-the-art in AM supply chains and AM user cases, introduced a novel additive manufacturing as a Service (AMaaS) system, and pointed out the challenges that need to be addressed to facilitate its adoption. We find that there have been very few efforts to incorporate 3D-printers to manufacturing processes in a flexible and adaptive fashion, particularly on the use of mobile AM deployment. We have also identified several use cases that accommodate both centralized and distributed business models. Based on all these findings, we propose a much needed system architecture, our AMaaS. The proposed architecture provides a market platform that incentivizes both manufacturers and buyers to simplify their supply chains for more convenient access to AM technologies. By leveraging the blockchain, the proposed architecture establishes trust among the participants and provides resiliency. Finally, we have identified critical research issues on AMaaS design, particularly on the joint market and control mechanism design, blockchain design, and facility placements. We hope that this paper offers design guidelines on how to develop an effective AM supply chain for advanced manufacturing industries.

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