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Blockchain-based Shared Additive Manufacturing

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ABSTRACT

Today, globalized markets require more resilient and agile manufacturing systems, as well as customized and virtualized features. Classical self-standing manufacturing systems are evolving into collaborative networks such as Cloud Manufacturing (based on centralized knowledge and distributed resources) or Shared Manufacturing (based on fully decentralized knowledge and distributed resources) as a solution to ensure business continuity under normal as well as special circumstances. Additive Manufacturing (AM), one of the enablers of Industry 4.0 (I4.0), is a promising technology for innovative production models due to its inherent distributed capabilities, digital nature, and product customization ability. To increase the adaptivity of distributed resources using AM technology, this paper proposes a mechanism for sharing workload and resources under unexpected behaviours in the supply chain. Smart contracts and blockchain technology in this concept are used to provide decentralized, transparent, and trusted operation of such systems, which provide more resilience to disruptive factors. In this paper, the proposed Blockchain-based Shared Additive Manufacturing (BBSAM) protocol, ontology, and workflow for AM capacity pooling are discussed and analysed under special conditions such as anomalous demand. Discrete-time Python simulation on a real Italian AM market dataset, also provided, is available on GitHub.

1. Introduction

Highly agile and resilient networks that adapt reactively to disruptive events and constantly higher pace of changes in customer demand become one of the most crucial trends in recent intelligent manufacturing systems research (Dolgui et al., 2020). In this context, the move toward a higher number of variants and more customizations complicates the struggle for machine utilization (Freitag et al., 2015), but approaches that propose manufacturing as a service (Catarci et al., 2019) are emerging as a promising field to address such challenges.

As highlighted by Kusiak, 2019 , while customers expect personalization of products and on-time delivery, the manufacturing industry is affected by uncertainties of different origins. In this context, resilience plays a fundamental role and can be defined as the ability of a system (in this case, a manufacturing system) to recover from an undesirable state and respond to the desired state (Hollnagel et al., 2006; Qin et al., 2022). In this framework, we propose the application of Industry 4.0 (I4.0) technologies (Lupi et al., 2022) such as Additive Manufacturing (AM) and blockchain in a new concept of a shared production environment that ensures better resilience compared to isolated approaches.

Shared production can be achieved via centralized or decentralized modes. Decentralization refers to the distribution of authority and control across a network of participants, rather than being concentrated in a central entity or authority (i.e., centralization). One of the key benefits of decentralization is its resilience to the shutdown or corruption of a node (Appio et al., 2018). In a centralized system, the failure of a central authority can lead to the entire system collapsing or becoming vulnerable to manipulation. Blockchain technology is a prime example

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of decentralization in the realm of information systems (Tumasjan and Beutel, 2019). It achieves this by utilizing a distributed ledger that is maintained by multiple nodes, each independently verifying and recording transactions. In a blockchain network, the data is replicated and stored across multiple nodes, making it highly resistant to shutdowns or corruption (Guo et al., 2020). Despite its advantages, decentralization also exposes blockchain to certain drawbacks. One significant concern is the susceptibility to attack vectors, such as the 51 percent attack. This attack occurs when a single entity or a group of colluding participants controls most of the network's computational power, allowing them to manipulate transactions and undermine the integrity of the blockchain. Furthermore, although the lack of trusted intermediaries in distributed systems enhances transparency, it may also limit the ability to resolve disputes or provide oversight when needed (Hawlitschek et al., 2018).

More specifically, comparing centralized and decentralized approaches, blockchain as a form of decentralization possesses specific features. One notable feature is the concept of an immutable database, where once a transaction is recorded on the blockchain, it becomes extremely challenging to alter or tamper with. This immutability is achieved through cryptographic mechanisms that ensure the integrity and transparency of the data. Additionally, blockchain networks commonly employ consensus algorithms, such as proof-of-work or proof-of-stake, to validate and agree on the state of the blockchain (Lee et al., 2019). These algorithms introduce a level of trust and security by requiring participants to provide computational resources or stake their own assets to validate transactions. Another significant weakness of blockchain is the energy consumption associated with proof-of-work consensus algorithms, which has raised concerns about its environmental impact. Additionally, the scalability of blockchain networks remains a challenge, as the requirement for consensus and replication across multiple nodes can limit the speed and efficiency of transaction processing. A detailed analysis of the characteristics of both centralized and decentralized approaches, as well as the specific features and weaknesses of blockchain, allows a comprehensive understanding of the advantages and limitations of blockchain as a form of decentralization (Rožman et al., 2021a; Rožman et al., 2021b).

The manufacturing industry has witnessed significant advancements in information systems, which have led to more efficient and streamlined processes. One critical aspect of manufacturing operations is the processing of initial demands, as it directly affects resource deployment. Variations between distributed and centralized systems in terms of demand processing and resource allocation can lead to advantages and drawbacks associated to each approach.

In a centralized information system, demands are typically routed through a broker who acts as an intermediary between customers and manufacturers. The broker collects and consolidates demands from various sources, allowing manufacturers to access a centralized pool of potential orders. Manufacturers can review the demands and negotiate terms with the broker before committing resources to fulfill the orders. This configuration offers several advantages, such as streamlined demand aggregation, centralized negotiation processes, and the ability to optimize resource allocation based on market trends (Oeser, 2015). However, the centralized nature of this system can introduce bottlenecks and delays in demand processing, potentially leading to suboptimal resource deployment and reduced responsiveness to market fluctuations.

In a distributed information system, demands are directly issued to manufacturers, who are responsible for their own demand acquisition and subsequent trading. This configuration eliminates the need for a central broker and allows manufacturers to interact directly with customers. By eliminating intermediaries, the distributed system offers the potential for quicker response times, enhanced flexibility, and reduced costs associated with brokerage fees. Additionally, manufacturers have more autonomy in selecting demands that align with their capabilities and strategic objectives. However, the absence of a centralized broker can lead to challenges in demand aggregation, coordination, and negotiation (Archimede et al., 2014). Manufacturers may face difficulties in acquiring a sufficient volume of demand to fully utilize their resources efficiently, and the absence of a centralized entity may result in limited market visibility and potential trading inefficiencies.

The choice between centralized and distributed systems for demand processing significantly impacts resource deployment in manufacturing. In centralized systems, resource allocation decisions are often made based on consolidated demand information provided by the broker. This allows manufacturers to optimize resource utilization by aligning production capacities with aggregated demands. On the other hand, distributed systems enable manufacturers to exercise greater control over the selection of demands, potentially resulting in a higher degree of resource specialization and customization. However, this may also lead to resource underutilization if manufacturers struggle to acquire an adequate volume of demand. An understanding of the advantages and drawbacks of each approach is crucial for developing a suitable protocol achieving optimal resource deployment in response to customer demands and market dynamics. The purpose of this paper is to explore hybrid models that combine the strengths of both approaches.

In line with the general concept of resilience highlighted earlier, a wide range of detailed definitions have been proposed in the literature (Moghaddam and Deshmukh, 2019). In the current work, resilience is assumed as the ability of the system "*to absorb strain and improve functioning under challenging internal and/or external conditions*" (Vogus and Sutcliffe, 2007). Section 2 proposes a shared AM protocol that considers both functional and structural resilience.

Functional resilience can be associated with a specific business-related uncertainty factor (e.g., customer demand variability) and measured by performance attributes from the literature, such as service level (Annarelli et al., 2020) and productivity (i.e., machine utilization) (Kusiak, 2019). These aspects are analysed in detail in Section 3 using an experimental simulation.

On the other hand, structural resilience is related to the conventional concept of disruptive events that can occur at both physical and cyber levels (e.g., unpredictable problems in energy, materials, assets and processes, transportation, supply chain, and communication) (Kusiak, 2019). As additional contribution, this paper focus on the structural resilience incorporating a Blockchain-Based environment into the proposed Shared Additive Manufacturing (BBSAM) protocol for a secure environment and standardized workflows (Babiceanu and Seker, 2016). Theoretical considerations are provided in the related Section 2.3.1, but simulation of structural resilience is outside the scope of this paper. The research questions (RQs) underlying this thesis can be summarized as follows.

RQ1:*Can atheoretical protocol be developed, through the implementation of a novel production model, to: (i) increase the service levels and machine utilization of AM systems; (ii) provide functional resilience to uncertain customer demand; (iii) provide structural resilience to disruptive factors?*

RQ2:*Is it possible to quantitatively evaluate the functional resilience of the proposed protocol and compare it to an isolated AM system?*

Fig. 1 provides a brief overview of the paper and highlights the main concepts and issues addressed.

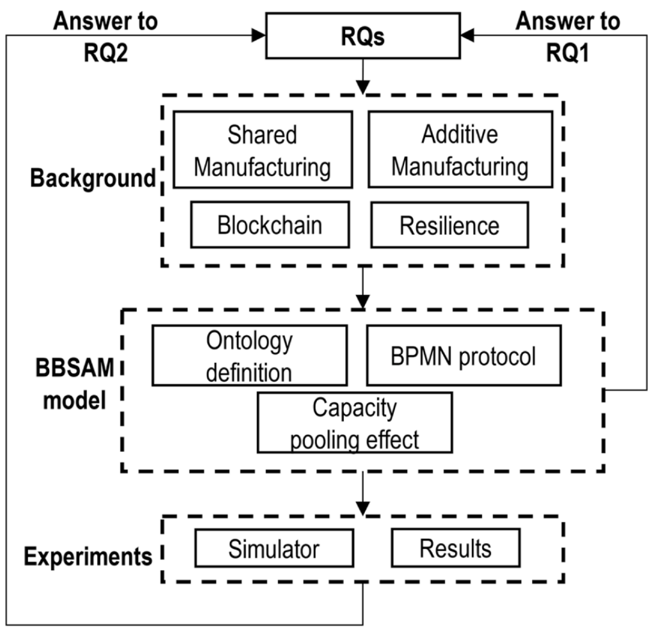

Fig. 1. Provides a brief overview of the paper and highlights the main concepts and issues addressed.

1.1. Shared manufacturing and blockchain

The literature shows that resource sharing is the critical foundation for new efficient production approaches. Shared resources belong to enterprises with independent accounting and different geographic locations but may be mutually needed.

The problem of shared resources is studied as a hotspot issue because resources seem to be limited in a single company to meet the rapidly changing market environment (Archimede et al., 2014). As highlighted by Szaller and Botond, 2021, resource sharing generally improves resource utilization among participants, and decentralizing authority to individual production sites and suppliers can be beneficial as well, especially for highly customized products (Mourtzis et al., 2012). In this respect, the main purpose of a Shared Manufacturing system is to increase the use of unused resources by moving from classical self-standing production systems to collaborative manufacturing networks (Camarinha-Matos et al., 2009). In this framework, the rise of I4.0 and the convergence of the digital and physical worlds (i.e., digital twin (Roucoules and Nabil Anwer, 2021) is increasingly, if not radically, changing the production networks, leading to a progressive opening of company boundaries and collaborative solutions (Botond et al., 2018; Tao et al., 2017; Appio et al., 2018).

Compared with the existing concept of Cloud Manufacturing, the concept of Shared Manufacturing focuses on maximizing the utility of things and services (to improve sustainability), while the purpose of Cloud Manufacturing is mainly centred to increase the convenience of inter-company collaboration (Yu et al., 2020). From the perspective of the sharing economy, Shared Manufacturing ensures the right of the manufacturing provider to self-organize by enabling manufacturers to organize themselves in a peer-to-peer (P2P) manner.

In these new production systems, which have been defined as one of the most critical organizational forms, bias and trust between different parties play an essential role (Lanza et al., 2019). As stated by Vatankhah Barenji, 2021, collaboration is a strategic and practical way to gain a competitive advantage for digital firms, but the core enabler of the collaboration is "trust" among agents. Among the new digital technologies that deliver trust, employing blockchain in Shared Manufacturing enables decentralized coordination between providers and consumers of the manufacturing services (Lee et al., 2019). Furthermore, the immutability of records improves accountability (Papakostas et al., 2019). Shared Manufacturing platform based on blockchain technology is presented in the concept of Blockchain-based Shared Manufacturing (BBSM) which was first defined in (Yu et al., 2020).

1.2. Sharing in Additive manufacturing

According to the process taxonomy provided by Hayes and Schmenner, 1978 and adapted in Table 1, manufacturing process types (i.e., rows) range from custom manufacturing at the top (e.g., project, job shop and batch) to mass production at the bottom (e.g., production lines and continuous flow), passing through hybrid approaches. The specific demand features (Table 1, last column) are the key factors in defining the production process features (e.g., physical flow, key management tasks, and dominant competitive mode).

For example, scenarios characterized by uncertainty, heterogeneity, high variability, low volumes, frequent design changes, and short demand life cycles (i.e., highlighted area, Table 1) often lead to overcapacity (i.e., unused resources) or capacity reduction (i.e., rejected orders) in Small and Medium-sized Enterprises (SMEs). The functional resilience of such manufacturing systems deserves special attention for new technological processes such as AM (Guo et al., 2020) that lead to ever higher levels of customization (e.g., personalization).

AM enables a high degree of flexibility and agility in manufacturing personalized end-use parts for medical, aerospace, automotive and other

Table 1
Process type (i.e., rows) and features (i.e., initial three columns) as well as demand features (i.e., last column) in the field of operation management according to the diagonal of product-process matrix (Hayes and Schmenner, 1978) and additional attributes extracted from (Safizadeh et al. 1996). Demand features that characterize custom manufacturing process types have a major impact on functional resilience of such production systems. Specifically, AM can be classified in the top row of the table (i.e., project/job shop) as a representative technology that deals with these specific process and demand features.

			Process features			Demand features
			Physical flow	*Key management tasks*	*Dominant competitive mode*	
Process type	***Custom manufacturing***	***Project/job shop***	jumbled flow	bidding delivery	custom design quality control	uncertain heterogeneous
		Job shop/batch	jumbled flow but a dominant flow exists	product design flexibility fast reaction	high margins service general purpose machines	high variance low volume frequent design change short lifecycle
	Mass production	***Production line***	connected line flow few major products	balance process stages	standardized design inventory backup suppliers	certain homogeneous low variance
		Continuous flow	automated and rigid flow	running equipment at peak efficiency materials management	vertical integration specialized equipment economies of scale	high volume slow design changes longer lifecycle

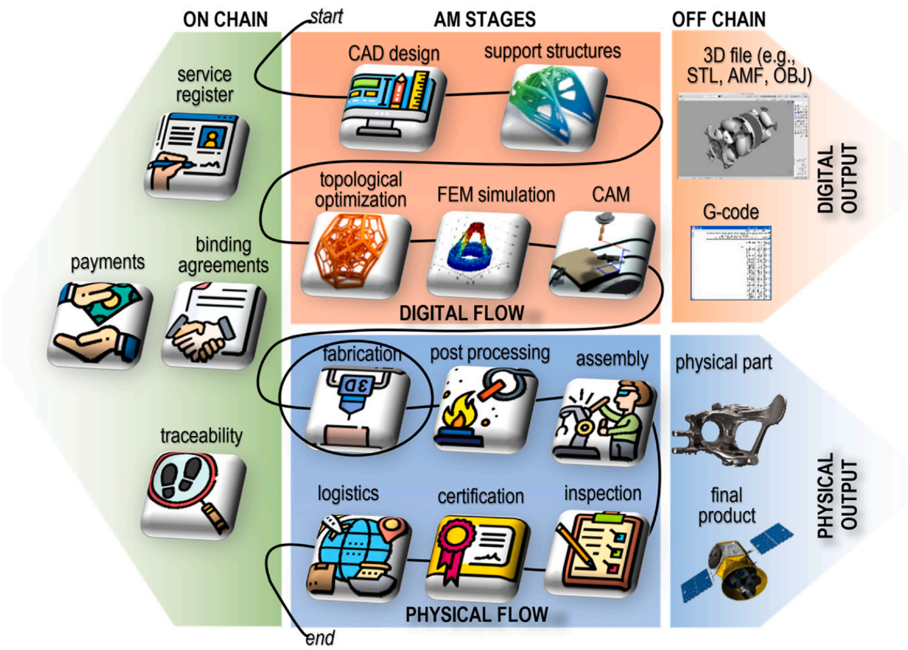

Fig. 2. Chronological stages (centre) for the development of a typical (AM) product. Outputs off chain (right) can be ideally provided by a different network of providers, following on chain transactions (left). While on chain transitions are ensured to fulfil high degree of security due to blockchain technology proposed in our model, non-disclosure requirements for the digital output are not considered in the current work but could be included in the on chain aspects if necessary. The fabrication level in the highlighted area is analyzed in depth in Section 3.

industrial applications using polymers, metals, alloys and composites.

Compared to traditional general-purpose subtractive machines (e.g., Computerized Numerical Control (CNC)), which are well suited for one-off, job-order, and low-volume production, AM machines share similar characteristics. Despite the similarities in process characteristics to project/job shop process types (Table 1), AM offers novel and distinctive features that appear to facilitate flexible and collaborative production networks and ultimately increase machine utilization and customer service in a customer-centered manufacturing paradigm (Zhang et al., 2018).

In particular, Fig. 2 (center and left) shows the AM stages and associated output, as well as the physical and digital AM flow (Vaneker et al., 2020). Starting from the top left, the initial AM product development stages (digital flow) utilize Computer Aided Design (CAD) and Finite Element Modeling (FEM) software for part and process definition and verification, including topological optimization and support structures design. The standard output format for a three-dimensional (3D) model in these stages is Standard Tessellation Language (STL) and object (OBJ) files. Computer Aided Manufacturing (CAM) can be thought of as a module (usually included in AM software) for the slicing of the 3D model and the generation of the file readable for the AM machine (e.g., G-code). From the fabrication stage, the flow switches to physical part realization including post processing (e.g., heat treatment, machining, chemical treatment), assembly for final product inspection, quality control, certification, and logistics activities (Frazier, 2014). To conclude the overview of Fig. 2 (left), all the product development stages from start to end, could be associated with blockchain technology as shown by the black thread. This approach guarantees recording transactions in a service registry, binding agreements, ensuring traceability, and secure payments involving multiple agents.

In a nutshell, AM simplifies the manufacturing procedure into a unique production activity based on a layer-wise approach (Frazier, 2014). It also shortens the supply chain for manufacturing parts (Zhu et al, 2020). In addition, as AM transitions to I4.0, almost the entire process is controlled by software, making it highly digitized and maximizing the possibilities of digital twin and blockchain applications at different stages of product development (He & Bai, 2021; Guo et al., 2020).

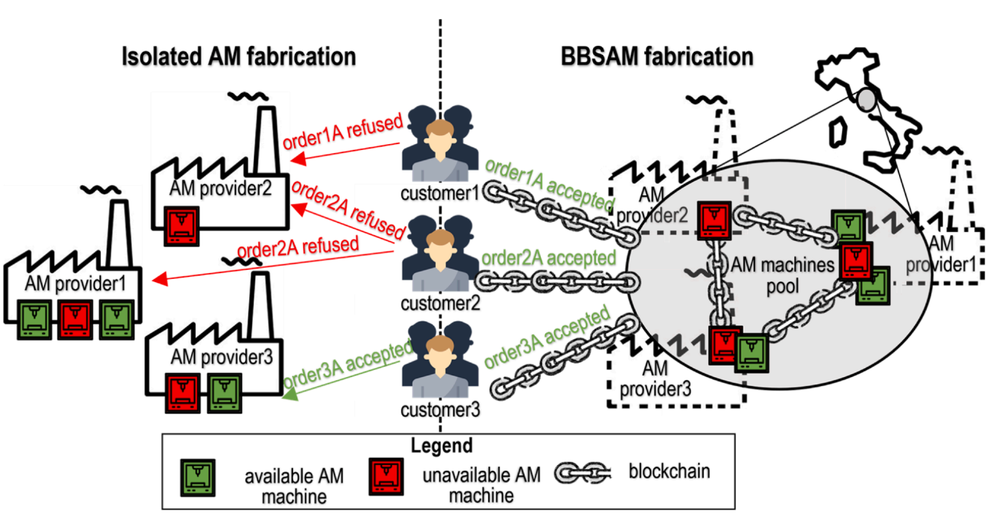

Fig. 3. Orders refused in an isolated AM system (left) can be accepted in a BBSAM trustful environment, which enables pools of AM machines made by different providers to share unused resources (right). A pool of AM machines, represented by the highlighted area, can be viewed as a group of AM providers (e.g., a region of Italy in the inset) sharing resources, calendars, and orders within the collaborative network to absorb unexpected conditions and improve functional resilience (i.e., maximize the service level and machine utilization as the business demand fluctuations increases) as well as structural resilience (i.e., guarantee a secure transaction environment and standardized workflow to disruptive events). Further market segmentation of potential providers is possible on an anonymous basis by technology, cost, and quality level.

1.3. Introduction to the proposed model

This paper focuses on the AM fabrication stage in Fig. 2 (highlighted area), but can be generalized to any other AM stage highlighted in Fig. 2 (e.g., CAD (re)design, post-processing, testing).

In the following, we briefly introduce the two agents and the main concepts related to the proposed BBSAM model to provide valuable answers for the industrial application of the two research questions (RQs) defined in the outline. The first agent is the AM provider. From here on, the AM provider can be an individual, an organization, an enterprise, or a third party that owns and provides the manufacturing resources and abilities (Tao et al., 2017) involved in the AM fabrication stage. The second agent type is the consumer, who purchases the use of the AM service on an operational expense and due date basis according to his or her needs (Tao et al., 2017).

Using the highly simplified example in Fig. 3, we summarize the main concepts of the proposed manufacturing model and compare isolated AM and BBSAM manufacturing systems. In a scenario with isolated AM manufacturing (left side, Fig. 3), AM provider2 cannot fulfil customer1′s and customer2′s orders (i.e., order1A and order2A) internally because its own AM machines are not available (no production capacity). Due to limited production capacity of AM provider3 and AM provider2, both customer1 and customer2 have their orders rejected. Only customer3 has his order accepted (i.e., order3A). Considering the previous scenario, the service level of the system can be calculated as the number of accepted orders over the total number of orders = 1/3 ~ 33% (order2A is counted only once because it is the same order rejected by different providers), while the machine utilization can be calculated as the sum of unavailable and assigned AM machines in relation to the total AM machines = (3 + 1)/6 ~ 66%.

If we switch to the BBSAM fabrication scenario (right side, Fig. 3) and consider the same assumptions on machine availability and customer demand, even if AM provider2 has no available AM machines, he can forward order1A to another AM provider with available capacity and accept the customer order. This can be achieved through a virtual pool of providers connected by a smart contract on the blockchain, sharing resources, calendars, and orders within the collaborative network (Botond et al., 2018). Similarly, order2A can be accepted. In this case, the service level is 3/3 = 100% and the machine utilization is (3 + 3)/6 = 100%.

To summarize, **RQ1** (especially in the functional resilience part) and **RQ2** are triggered by the variability of peaks and urgency of AM customer demands (e.g., spare parts (Durão et al., 2016)) which require to hold an amount of safety production capacity, which turns out unexploited; this also applies to on demand service companies. Despite the paradigm shift from isolated or self-standing to decentralized AM production (Mai et al., 2016) theorized in recent years, practical Shared Manufacturing protocols remain far from being defined for real-world scenarios. The objective of the paper is to provide a novel production model that increases system performance (i.e., service levels and machine utilization) and provides functional resilience to uncertain customer demand and structural resilience to disruptive factors.

The logical structure of the paper provided in Fig. 1 is detailed in the following remainder as follows. Section 2 provides a brief recall of the core concept behind the proposed BBSAM model along with a detailed Business Process Model and Notation (BPMN) diagram, related ontology and pseudocode, addressing **RQ1**. The simulation step (answer to **RQ2**) is carried out using a real dataset of metal AM (Frazier, 2014) machines in Italy (Anonymous market leader, personal communication, 2021) in Section 3. In this section we quantitatively evaluate machine utilization and service level metrics comparing isolated AM production and BBSAM systems. To conclude, Section 4 points out promising future directions in the field and provides a summary and outlook of the paper.

2. BBSAM fabrication stage

2.1. Capacity pooling effect

The shared AM system is a flexible flow shop-like environment in which AM providers represent a geographically distributed pool of machines subjected to overheads, logistical transportation times, and costs. Each machine has a finite daily capacity (i.e., it can process orders sequentially or simultaneously, depending on the topology optimization). Each AM provider i = 1…n sets its production capacity (i.e., the number of AM machines) based on historically received demand x_i. If each provider just satisfies its own demand and wants an $\alpha = 95\%$ service level, an overproduction capacity of $z_{95\%}\sigma$ is required. With a given demand variability σ_i and average demand μ_i for provider I, the safety production capacity leads to an underutilization of the AM machines of $z_{95\%}\sigma_i / (\mu_i + z_{95\%}\sigma_i)$.

In a shared approach (i.e., capacity pooling (Oeser, 2015)) it is possible to increase the actual capacity to serve a bigger demand with the same number of machines or reduce the number of machines to maintain the same service level. According to (Oeser, 2015), this aspect of capacity pooling is associated with the reduction of overall

$$\sigma_{global} = \sqrt{\sum_{i=1}^{n} (\sigma_i)^2 + 2\sum_{i=1}^{n} \sum_{i<j}^{n} \sigma_i \sigma_j \rho_{ij}}$$

where ρ_{ij} is the correlation coefficient of the random variable for the company I and j. It can be formally shown that $\sigma_{global} \leq \sum_{i=1}^{n} \sigma_i$because of the subadditivity property of the square root of non-negative real numbers. Please note that only if all the random demands x_i are perfectly positively correlated (i.e., $\rho_{ij} = +1, \forall i,j$) or if at least n-1 $\sigma_i = 0$, then $\sigma_{global} = \sum_{i=1}^{n} \sigma_i$. Otherwise, capacity pooling leads to variability reduction. The highest possible variability reduction is achieved if there are negative correlations (i.e., $\rho_{ij} = -1, \forall i,j$).

2.2. The formal BBSAM protocol

Fig. 4 illustrates the fundamental concepts and static relationships of the proposed BBSAM protocol as an ontology diagram used for the BPMN representation (Fig. 5) and pseudocode definition (Fig. 6).

In the ontology each concept is enclosed in a rectangular shape. Concepts are connected by relationships, represented with labelled directed edges. Some concepts are also characterized by properties listed in lowercase letters. Specifically, in the middle, an *AM Machine guarantees* an *Availability* in a *time horizon;* and *is owned by* a *Provider*. A

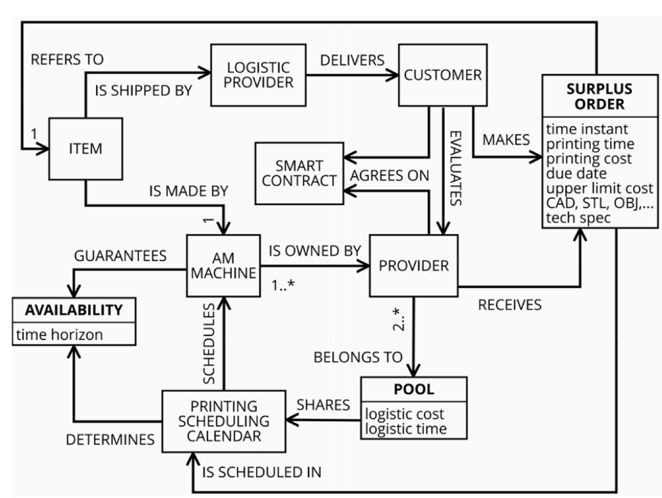

Fig. 4. Ontology diagram as a static representation of the problem domain, providing all the concepts used in the dynamic view of Fig. 5 and the procedural steps of Fig. 6.

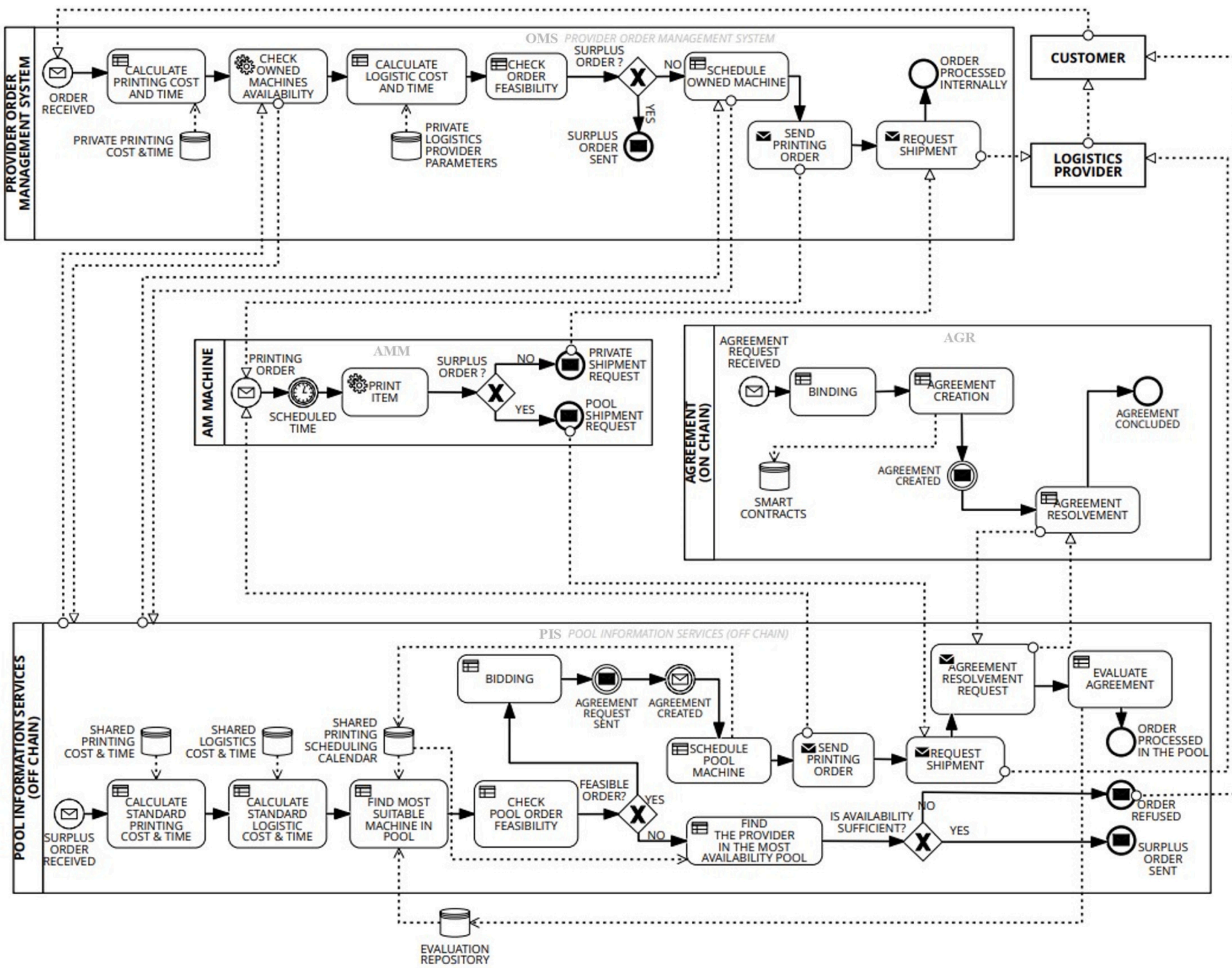

Fig. 5. The BPMN protocol. Concepts definitions are provided in Fig. 4. In BPMN, an event, an activity, a decision node is represented by a circle, a rounded box, a diamond, respectively. Sequence flow and data flow are represented by solid and dotted arrows, respectively. Data storage is represented by a cylinder. Finally, a rectangular area represents a different actor or system.

Provider belongs to a *Pool*, which is characterized by the same standard *logistic cost* and *time*; and *shares* a *Printing scheduling calendar* to *schedule* the *AM machine* and to *determine* its *Availability*. The *Provider receives* a *Surplus order*, characterized by *time instant, printing time* and *cost, due date*, *upper limit cost*, and other technological properties. The *Surplus order* is scheduled in the *Printing scheduling calendar.*

On the top, a *Customer makes* a *Surplus order*, which *refers to* an *Item* that *is made by* an *AM machine. Customer* and *Provider agree on* a *Smart contract*. Finally, an *Item is shipped by* a *Logistic provider* which *delivers to* a *Customer* who *evaluates* the *Provider's* service execution. A crucial assumption in the proposed system is that limited parts could be printed on a single AM machine considering AM providers have a standard quality (i.e., identical machines).

Fig. 5 shows a simplified protocol of BBSAM in a standard graphical BPMN representation. The protocol is built on the ontology in Fig. 4 and covers only the essential aspects of the proposed approach for the sake of readability. The BPMN is based on a solid mathematical foundation to enable the execution, simulation, and automation of consistency checking (Cimino et al., 2017). It is also suitable to standardize and facilitate communication between all stakeholders. Overall, ontologies and BPMN can help overcome language barriers between participating members, enable internal integration of information systems, provide semantic access to knowledge, and coordinate collaborative actors with different knowledge backgrounds (Appio et al., 2018).

In BPMN, a rectangular area represents a participant who takes part in a protocol via message exchange. In each rectangular area, the protocol is managed via events, activities, and decision/merge nodes, represented by circles, rounded boxes, and diamonds, respectively. Sequence flows and data flows are represented by solid and dotted arrows, respectively. Finally, data storages are represented by cylindrical shapes.

Specifically, the protocol starts on the top left when an order is received by the provider in the Order Management System (OMS) module and ends in the same provider if its AM machines and logistics providers guarantee sufficient availability and feasibility. Otherwise, it is considered a surplus order, associated to the most suitable machine in the pool and processed according to the protocol in the Pool Information Services (PIS) module. After bidding, the binding and the creation of the agreement activities are carried out in the blockchain (on the middle-right) agreement (AGR) module, then the surplus order is scheduled by the pool protocol (on the bottom), and finally produced by the AM machine protocol (on the middle-left) in the AM machine (AMM) module. After the shipment, the agreement is resolved in the blockchain (on the middle-right), and a final evaluation of the executed service is provided by the customer (on the bottom-right). According to the PIS module, if the order is not feasible, it is sent to a provider also belonging to another pool with more availability, and so on. It is worth noting that when moving to a different pool, different shared costs and time can be

```
Provider Order Management System (OMS)
1.      Customer order received by OMS;
2.      OMS calculates printing cost & time;
3.      OMS checks owned machines availability;
4.      OMS calculates logistic cost and time;
5.      OMS checks order feasibility
6.1     if not surplus order
6.1.1     OMS schedules owned machine
6.1.2     OMS sends printing order → AMM
6.1.3     OMS requests shipment to logistics provider
6.1.4     Order has been processed internally
6.1.5     end
6.2     if surplus order
6.2.1     surplus order is sent by OMS → PIS
6.2.2     end

AM Machine (AMM)
1.      Printing order received by AMM
2.      when scheduled time has elapsed
3.      AMM prints item
4.1     if not surplus order
4.1.1     AMM sends private shipment request → OMS 6.1.3
4.1.2     end
4.2     if surplus order
4.2.1     AMM sends pool shipment request → PIS 6.2.6
4.2.2     end

Pool Information Services (PIS) – off chain
1.      Surplus order received from OMS
2.      PIS calculates standard printing cost & time
3.      PIS calculates standard logistic cost & time
4.      PIS finds most suitable machine in pool
5.      PIS checks pool order feasibility
6.1     if order not feasible
6.1.1       PIS finds provider in most availability pool
6.1.1.1     if availability sufficient
6.1.1.1.1     surplus order is sent by PIS → PIS
6.1.1.2     if availability not sufficient
6.1.1.2.1     order refused by PIS
6.1.1.2.2     end
6.2     if order feasible
6.2.1       PIS carries out bidding
6.2.2       agreement request sent by PIS → AGR
6.2.3       agreement created
6.2.4       PIS schedules pool machine
6.2.5       PIS sends printing order → AMM
6.2.6       PIS requests shipment
6.2.7       PIS requests agreement resolvement → AGR 5
6.2.8       PIS evaluates agreement
6.2.9       order processed in the pool
6.2.10      end

Agreement (AGR) – on chain
1. agreement request received
2. AGR carries out binding
3. AGR carries out agreement creation
4. agreement is created → PIS 6.2.3
5. AGR carries out agreement resolvement
6. agreement concluded → PIS 6.2.8
7. end
```

Fig. 6. Pseudocode for the BBSAM protocol presented in Fig. 5.

applied. Consequently, the number of consecutive pools that can be reached by an order is limited by the due date and upper limit cost. Finally, Fig. 6 presents the procedural steps of the proposed protocol in the form of a detailed pseudocode derived from Fig. 5.

2.3. Blockchain as an enabler of resilience in Shared manufacturing

The main task of the BBSAM protocol is to enable each user to share their unused available resources. Connecting and organizing such a dispersed group of entities at the global level can be a major challenge. This issue is usually addressed by centralized platforms, but problems arise with trust in the platform provider (Hawlitschek et al., 2018).

Digital platform business models are a prime example of winner-takes-all markets, where economies of scale and profit maximization foster market structures dominated by powerful platform owners (Brynjolfsson and McAfee, 2014). There is a generalized concern that platforms can control which connections are made and which users are able to make connections by altering the algorithm (Sutherland and Jarrahi, 2018). Ultimately, platform owners may use their power to establish or even enforce processes that can disadvantage users and the public (Tumasjan and Beutel, 2019). With smart contracts, blockchain technology enables the establishment of a platform that allows financial transactions and the transfer of information between users in a decentralized manner (Tumasjan and Beutel, 2019). Such a platform, where the terms of operation are known and transparent in advance and decisions are made decentralized, provides users equal opportunities to integrate into the system.

2.3.1. Structural resilience through blockchain technology

The decentralization of the platform and financial activities using blockchain technology can also increase the structural resilience of such an open manufacturing system. The structural resilience of the system can be increased in the following ways:

Prevent risk occurrence:

- The decentralized platform prevents cyberattacks from disrupting the system's operation. It is difficult to stop the network or change the written records.
- Due to the decentralized consensus, the majority of the participants must agree to prevent some users from participating in the system. Therefore, it is difficult for one user to prevent another user from participating in the system or to influence another user while participating.
- Transparent and immutable (trusted) records of past behaviour written on blockchain enable mitigation of collaboration with potentially malicious users in the system.

Reduce the impact of disruptions:

- Disruptions of platform operation are reduced. When some malicious actors disrupt platform operations (some nodes in the network), the rest of the platform is able to provide normal operations and immutable data records.
- Disruptions of the global manufacturing system (e.g., fluctuations in electricity prices) are reduced. Blockchain technology enables decentralized financial (DEFI) applications, therefore, new applications for mitigating the risks (e.g., for hedging against electricity prices) can be deployed and be used freely by any user (also individuals).

Improve the flexibility for coping with disruptions:

If the majority of the users in the system would act maliciously or normal operation of the platform would be disrupted, another platform can be almost instantly deployed and established on the blockchain network.

2.3.2. Blockchain in the proposed BBSAM protocol

In the proposed BBSAM protocol, AM machines follow the Shared Manufacturing Protocol (Rožman et al., 2021a) to publish their services and agreements with other providers and customers on the blockchain platform. Each pool is represented as a smart contract that AM providers

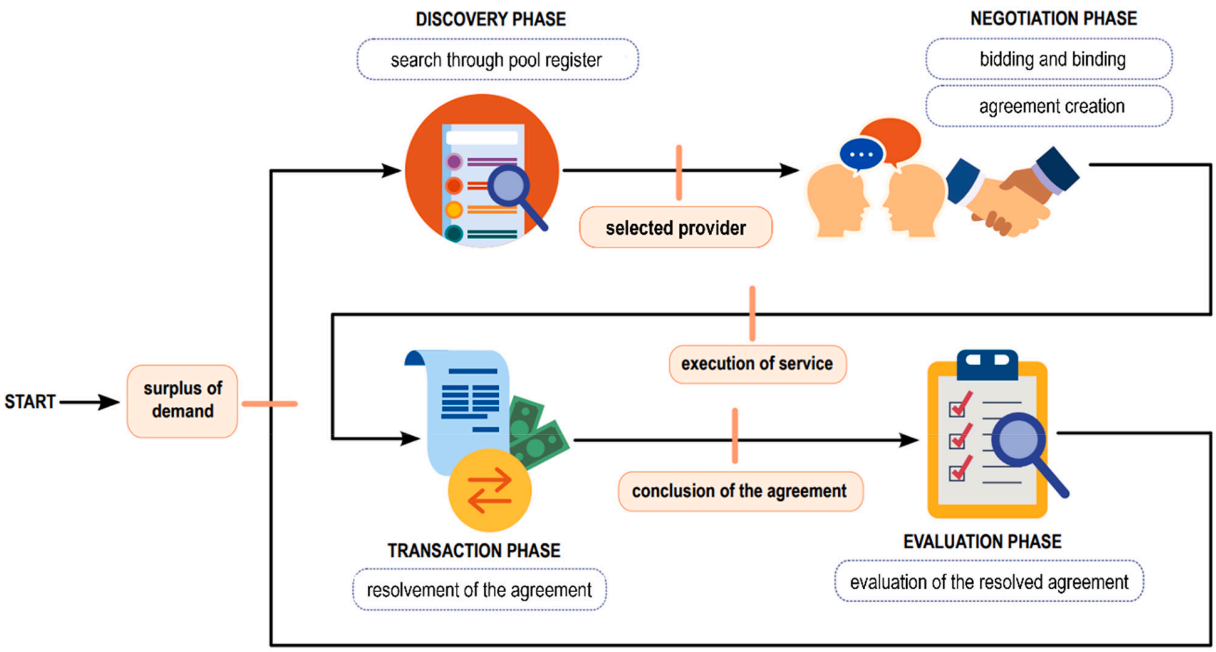

Fig. 7. Interaction of AM provider with pool over blockchain in BBSAM (on chain, Figs. 2, 4–6).

can join and offer their manufacturing resources. Pool properties (e.g., service type, geographic location of providers, input data requirements) are defined when a smart contract is created. Customers have access to a public list of all the resources in the pool with contacts of the providers. All agreements between providers and customers are also written to the smart contract of each pool.

AM provider identifies an appropriate pool based on pool requirements and joins with the registration process. A blockchain transaction assigns the provider a digital identity.

Digital identity is authenticated with the providers' personal private key according to the equation: $AccountAddress \ = > Sig_{user}(ID)$.

All provider communication with the smart contract is done via authenticated digital identity, preventing fraud impersonation. Customers also use providers' digital identities to securely (encrypted) communicate with providers. Cryptographic authentication and encryption are both integral parts of blockchain technology.

Fig. 7 offers a detailed view of the concepts provided in Fig. 2 and formalized in Figs. 4-6 related to the interaction process of an AM provider with the pool on the blockchain network. When demand surplus occurs, AM provider engages in the BBSAM protocol as a customer, and the discovery phase begins. AM provider creates a list of potential AM machines that would handle demand surplus, by searching through the register of available resources (i.e., shared printing scheduling calendar) in the pool. In the next phase (i.e., negotiation) bidding and binding processes are executed. First, the AM provider sends a request for service to all AM machines on the list together with specified input data requirements (e.g., CAD file, g-code, material, tolerances, interfaces, due date, upper limit cost). Then AM provider must select AM machine based on the conducted negotiations. When the AM provider (customer in the agreement) and selected AM machine (provider in the agreement) agree on conditions of service provision, they can bind the agreement on the smart contract.

The binding process is executed in four phases. First, the customer creates an agreement on the smart contract. The agreement specifies the customer's digital identity, provider's digital identity, service cost, and expiration date of the agreement. Then the customer commits to the agreement with a digital signature (i.e., digital identity). Next, the provider also commits to the agreement with a digital signature. Finally, the customer transfers payment funds for the service to the smart contract, which concludes the binding process. Binding offers providers a confident assurance that the payment will be executed at the end of the agreement as the funds had been transferred from the customer to the custody of a smart contract.

Table 2
KPIs related to the provider based on customer feedback and vice versa (Appio et al. 2018).

Agent type	KPI name	KPI description
Provider	(i) Adequacy	(i) the price is adequate to its yielded profit
	(ii) Reliability	(ii) the quality of the item/service matches its requirements
	(iii) Customization	(iii) personalized requirements can be implemented
	(iv) Expected delivery time	(iv) frequency and impact of delays
	(v) Post-sale service	(v) availability to damage repair and protection
	(vi) Communication	(vi) satisfied with the seller's communication
Customer	(i) Payment	(i) payment deadlines observed
	(ii) Changes	(ii) frequent running changes
	(iii) Communication	(iii) availability to interaction and meeting

During the transaction phase, the service provider delivers service to the consumer, and the resolvement procedure is carried out. The resolvement process begins when the expiry date of the agreement is reached. Provider and consumer report on the service execution and funds are released by the smart contract to the provider of the service if the service was executed according to the agreement. In case of dispute, the funds remain locked, and the agreement is publicly marked as unresolved. The immutability of the written records on the blockchain network offers uncensored information on past activities of AM providers in the BBSAM system and can be used in the evaluation phase to assess which provider is a potential candidate for selection next time when a surplus of demand occurs.

The behaviour management system is based on Key Performance Indicators (KPIs), which are given at the end of the collaboration between providers and customers in the form of relational feedback from 1 to 5 and are summarized in Table 2 according to Appio et al., 2018.

2.4. BBSAM features

To help readers summarize the main features implemented in our proposed BBSAM model, we provide a detailed summary with references to specific sections and figures and related work used in the development of the model.

Pooling effect: by using capacity pooling (Section 2.1), our model defines how unused manufacturing resources must be shared in the case of the BBSM concept (Yu et al., 2020).

AM resources: our model describes why AM is the most appropriate type of production process, according to capacity pooling, Shared Manufacturing, blockchain, Section 1 (Fig. 2 and Table 1).

Service booking and scheduling: the developed BBSAM model assumes that systems respond to surplus orders according to the protocol proposed in Section 2.2 (Figs. 5 and 6). According to the literature, the problem under consideration (e.g., maximizing machine utilization) can be formulated as a NP-hard scheduling optimization problem $P||(C_{max}, \sum U_i)$ where P is the capacity and speed of all machines, C_{max} is the makespan and $\sum U_i$ the number of tardy jobs (Graham et al., 1979; Rossi & Lanzetta, 2020; Rossi et al., 2014). Despite that, the optimization of the scheduling task is out of scope of the current work which is focused on the proposal of a novel business model.

Decentralization: blockchain technology is used in this concept to enable decentralized, transparent, and trustworthy operations (Hawlitschek et al., 2018; Rožman et al., 2021a; Rožman et al., 2021b; Tumasjan and Beutel, 2019). On chain phases and activities are described in detail in Section 2.3 and illustrated in Figs. 4–7.

Quality level: the proposed system assumes that a limited number of parts can be printed on a single AM machine, assuming that AM providers have a standard quality (i.e., identical machines), Section 2.2.

Costs: although transportation costs for complex AM parts are considered negligible with respect to printing costs, they are also considered in our BBSAM for the provider selection (they are considered fixed for a given pool), Section 2.2 and Figs. 4–6. As for the proposed protocol, it does not incur additional costs when using the blockchain platform as a common platform or only to process own transactions with customers.

Business process: in a system where autonomous business entities operate, sometimes competing and sometimes cooperating, it is necessary to pay attention to money streams (Zhu et al., 2020). For this reason, the proposed BBSAM protocol defines the flow of funds in the exchange of services and specifies how smart contracts enable the transaction of funds in exchange for provided services through a decentralized, secure, immutable, and transparent system, as summarized in Section 2.3 and illustrated in Fig. 7.

Behaviour management system: while blockchain technology can guarantee that the content of the information transmitted cannot be altered, it cannot guarantee that the intentions of agents cannot be altered (i.e., dishonest agents). Our paper provides a BBSAM protocol that (when followed) provides a clear view of past events (e.g., agreements) in the BBSAM system. Public access to these past events allows users of this system to evaluate the behaviour of other users in the system (Sections 2.2 and 2.3). The evaluation is based on the predefined KPIs listed in Table 2 (Appio et al., 2018).

Among several other benefits, this work aims to initiate novel research areas that will lead readers to new and promising research topics in the resilience of new manufacturing systems in the successive product development stages (Fig. 2). For example, ***decentralization*** capabilities could address not only the fabrication stage, but also the sharing of AM knowledge in early design phases (e.g., cooperative CAD design (ISO/ASTM 5, 2018), cooperative AM FEM simulation). In terms of ***quality level***, an enhanced BBSAM model could consider the labeling of different providers and customers based on the available and desired quality level (Seifi et al., 2017; ISO/ASTM 5, 2017). Unlike traditional ***scheduling*** methods that assume a local environment where all resources are in the same location, shared scheduling for distributed manufacturing is based on providers that realize the sharing information about unused manufacturing resources (Archimede et al., 2014). In this context, studies on distributed and optimized scheduling via meta-heuristics (Rossi and Dini, 2007) also deserve attention (Chen et al., 2019; Cheng et. al, 2020; Li et al., 2018). Further improvements could be achieved by considering the nesting of a surplus order in an already scheduled work volume via CAD geometric optimization (Chergui et al., 2018) in conjunction with fine scheduling and planning.

Section 3 will provide a simulation with real AM machines dataset comparing isolated and shared systems inspired by the BBSAM model.

3. Experiments

To answer RQ2, the performance of the proposed BBSAM model was compared quantitatively with an isolated AM fabrication, considering the distribution of installed Italian metal Powder Bed Fusion (PBF) machines according to the definition of the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) (ISO/ASTM 5, 2021).

3.1. AM machines data and simulator

Italian metal PBF machines data were collected by region and industry sector (i.e., aerospace, automotive, dental, energy, education, jewellery, medical, oil& gas, tooling) for a given brand. Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM) machines were used (Anonymous market leader, personal communication, Dec 2021).

A discrete-time simulator was developed to simulate the source of demand for each pool (i.e., a region in Italy) as the variability of demand increases. As highlighted by Lohmer et al., 2020 , the Blockchain enables more intensive collaboration through smart contracts and shared resources in Shared Manufacturing. The simulation of the blockchain environment is preliminarily explored in this paper, and the simulated model assumes honest agents that guarantee that everyone strictly adheres to the BBSAM protocol (i.e., including blockchain aspects) defined in Figs. 2, 4-7. The discrete-time simulator developed in Python code mimics the protocol defined in Figs. 5 and 6 (excluding the blockchain environment) and adopts the following deterministic rule for scheduling: schedules the job to the AM machine which presents the lowest machine utilization. The full description of the parameters and additional data on the entire Italian AM machines dataset are publicly available on GitHub[1].

In summary, the discrete-time simulator considers a unit of time as one hour. Each of the Italian regions is a different pool with n providers. Each provider has m AM machines. The internal (i.e., intra- pool) and the global (i.e., for the whole Italy) logistics time are set to 12 and 36 h, respectively. The production capacity of the AM machines is 24 h/day. Each order is executed by a single job whose production time corresponds to a Gaussian distribution (60 h average, 5 h standard deviation). Each order has a due date set at 120 + job duration.

The demand for orders was simulated, assuming a Gaussian distribution for each pool based on the Italian data. The average of orders μ in each pool was set at 60% of the installed capacity of that pool $\mu = 0,6(\sum_1^n m)24\text{h/day}*30\text{days}$, assuming a scenario where most providers require at least 95% service level in terms of due date adherence. The standard deviation of orders σ has been simulated at different values, from 0 to very high values (i.e., $\sigma = \mu$). The orders generated for the pool are randomly assigned to the providers inside the pool.

[1] https://github.com/galatolofederico/shared-manufacturing-simulator

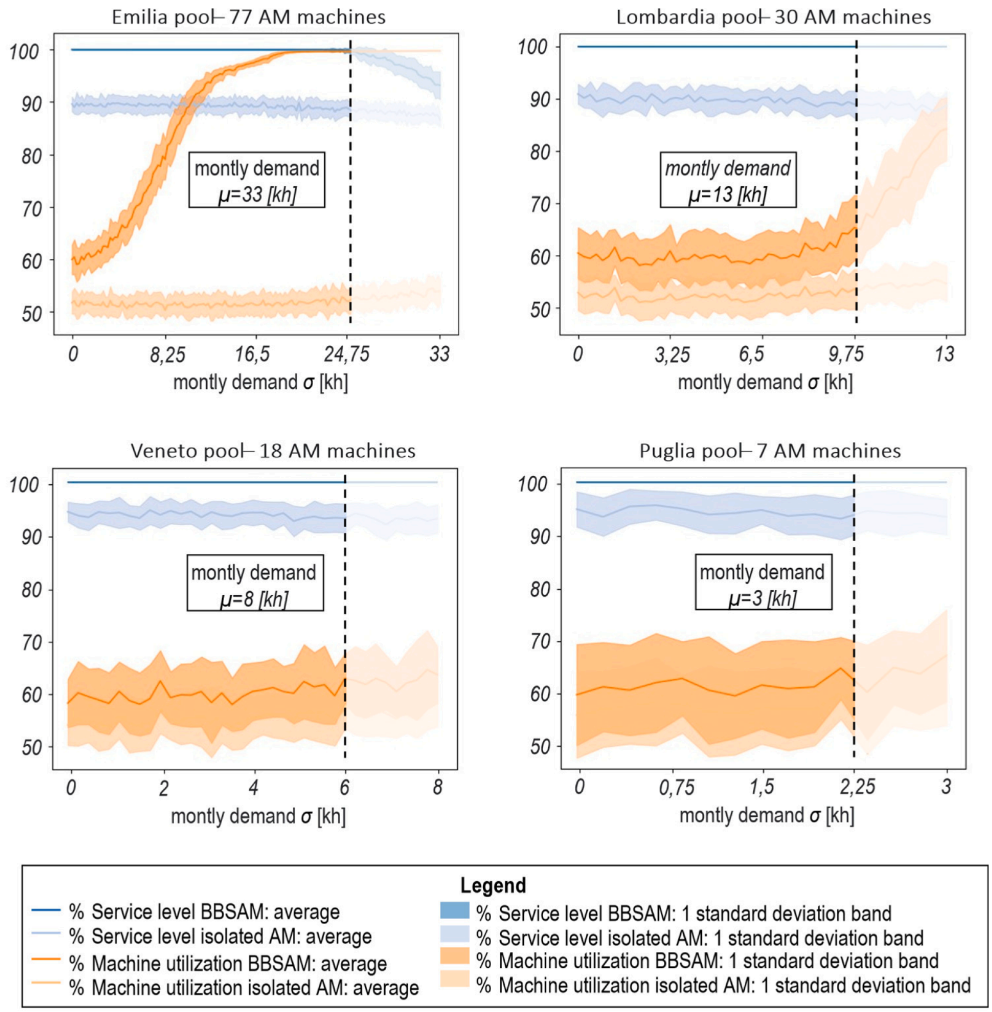

Fig. 8. The simulated service level and machine utilization as a function of the demand variability f(μ,σ) in kilohours after 30 repetitions for four pools (four Italian regions) having significant different number of AM machines. The average of orders μ in each pool has been set to 60% of the installed capacity of that pool. Variability σ was simulated using μ as a reference. Plots show 0,25μ increment of σ till $\sigma = \mu$. The lighter right areas after the dotted lines are an extrapolation (exaggerated variability over 0,75μ).

3.2. Simulator results

A total of 30 simulations were run for each pool over a 1000 h time horizon. The processing time for each of the 30 simulation runs is 15 min on an i7@5 GHz PC with 16 Gb ram. The simulation was run 30 times and averaged.

Fig. 8 shows the simulation results for four (out of the 17 available) pools presenting a significantly different number of AM machines. Additional simulations with different pools can be observed using the demo available at GitHub[1]. The graphs show the simulated service level (blue line and associated 1-standard deviation band) and machine utilization (orange line and associated 1-standard deviation band) as a function of the demand variation f(μ,σ) to highlight the improved performances of BBSAM over isolated systems (dark and light colours, respectively).

The x-axis represents the monthly demand variation in [kh], ranging from 0 (constant demand) to $\sigma = \mu$ (high variation, 0.15% peaks at 3 times μ). The y-axis represents the normalized service level and machine utilization in the range of 0–100%. Fig. 8 shows the better machine utilization proportional to the number of AM machines in a pool. The Emilia pool (77 AM machines) shows a rapid improvement compared to other pools with fewer machines. Moreover, the isolated system proves to be a lower bound in all cases (both service level and machine utilization show improvements or at least no deterioration for shared systems).

4. Discussion

As highlighted earlier, Fig. 8 shows how system performance increases proportionally to the number of AM machines in a pool. For example, the pool of the Emilia region with 77 AM machines shows a higher improvement in the machine utilization rate than the pools of the Lombardia, Veneto, and Puglia regions with 30, 18, and 7 AM machines, respectively. We hypothesize that this is due to the resilience of the system, which increases as the number of participants increases (Appio et al., 2018). When the pool size is less than 30, the pool size no longer affects the pattern, e.g., for regions such as Puglia (7 AM machines) or Veneto (18 AM machines).

BBSAM's service level seems to be almost constant at very high values across all pools, regardless of size. With particular attention to the Emilia region pool, it decreases very fast after the dashed line (i.e., σ realistic maximum value before exaggerated variability). This can be explained by the utilization rate reaching 100%.

Further experiments have shown that the shorter the order due date (i.e., the higher the urgency), the better the performance of BBSAM. Note that in Fig. 8, the due date is constant. This also suggests that BBSAM has structural and functional resilience due to the existing pool, meaning that in the event of multiple uncertainty factors in addition to customer demand variability (e.g., disruptions such as urgent demand, energy/material shortages, machine failure, or process, supply chain, and communication issues), another pool provider can take over.

Finally, based on the estimation, the machine utilization μ is expected to be 60% when $\sigma = 0$. On the other hand, the isolated production systems for the Emilia and Lombardia pools do not reach the expected value, as shown in Fig. 8. This is related to the adopted strategy for the random allocation of the generated orders to the providers within the pool during the simulation. For the same or aligned performance with low demand variation, a classical isolated production system might be preferable when switching to shared manufacturers due to the initial transition costs (e.g., monetary and non-monetary entry barriers related to the new infrastructure and procedures).

Although the proposed BBSAM model focuses on machine utilization and service level, it also includes some fundamental cost assumptions that are essential for enabling/disabling the pooling effect. The pooling effect relies on the ability of participants to freely trade their excess capacity or unfulfilled demands with others in the pool. This demand trading mechanism ensures that capacity shortages or excesses are balanced, enhancing overall system performance and profitability. However, when demand trading is restricted or not conducted at cost, the pooling effect may be compromised, leading to suboptimal resource utilization and decreased profitability.

More specifically, the model proposed in this paper considers two cost assumptions: (i) the same logistic cost and time in the pool; (ii) the printing time and cost, due date and upper limit cost of each surplus order. As a consequence, all providers are identical in the pool, except for the availability of their machines. When the availability is not sufficient to guarantee the due date, to move to another pool may result in different costs and time. Consequently, the number of consecutive pools that that can be reached by an order is limited by due date and upper limit cost.

The research proposed in this paper can achieve a novel perspective by adopting an extended costs model, in which the above assumptions can be progressively released to investigate the emergent effects. In the literature, a suitable costs model that can complement our research is made by (Hedenstierna et al., 2019). The authors work in the same context of 3D printer (3DP) pooling, with the same purpose of enabling capacity sharing via a novel outsourcing scheme. To manage demand variability, two fundamental mechanisms are proposed: (i) Order Book Smoothing (OBS), i.e., to gradually release orders to production; (ii) Bidirectional Partial Outsourcing (BPO), i.e., to share 3DP capacity by alternating between the role of outsourcer and subcontractor based on need. OBS manages the cases of limited capacity, while reducing responsiveness, whereas BPO shifts costs and delivery performance levels. Overall, the scheme achieves a higher resiliency to movements in both demand and price levels.

Specifically, the costs model adopted by Hedenstierna et al., 2019, is made by: machine capital costs, operating costs, material costs and labor costs. In terms of numerical analysis, the authors first analyze the main benefits of OBS and BPO on the costs breakdown by production system configuration. Further, they move from a cost-centric perspective to one of profitability, to find a combination of demand and price for which production system configurations become profitable. Similarly to our approach, to model different demand levels, demand variance is assumed to be proportional to the mean, to finally measure the effect of OBS and BPO, as well as the machine utilization is set at 60% according to the literature. The analysis revealed that: (i) given sufficient demand, 3DPs benefit from partial outsourcing without sacrificing responsiveness; (ii) OBS applies in most configurations but requiring slack between promised and processing lead times; (iii) the cost saving from OBS originates from existing inefficiencies or by reducing responsiveness; (iv) BPO supports trading excess capacity at low cost. Further research is warranted to explore strategies and mechanisms that enable efficient demand trading in distributed manufacturing systems, considering both operational and economic factors.

5. Summary and outlook

The Blockchain-based Shared Manufacturing (BBSM) concept has recently been proposed in the literature. Its application to Additive Manufacturing (AM) has been investigated here, presenting a novel Blockchain-based Shared Additive Manufacturing (BBSAM) model that explores the peculiarities of an emerging group technology such as AM, which can benefit from sharing the high investment and versatility of machines for resilience improvement (**RQ1**). The approach is based on the capacity pooling method, in which pooled capacity increases utilization in unexpected circumstances (e.g., demand fluctuations or disruptive events). An ontology of the problem domain is first created to facilitate pooling, which serves as the basis for a pooling protocol developed in a Business Process Modeling and Notation (BPMN) language and supported by blockchain technology. This approach uses smart contracts and blockchain technology to ensure the decentralized, transparent, and trustworthy operation of such a system for structural resilience. This approach is then tested with a discrete event simulation in Python and using the example of several AM machine pools in Italian regions and compared to a baseline scenario without shard resources (**RQ2**).

Developed code for simulation and Italian AM data are available at Github.

The main result is that optimized AM machine utilization and higher service levels are positively correlated with increasing demand volatility when capacity pooling (or shared systems) are introduced. As experimentally shown, the increased functional resilience of shared systems seems to be significantly above a certain number of AM machines.

The proposed BBSAM model can be improved using the identified attributes (listed in Section 2.4). Various peculiar ancillary activities during the AM product and process development also have an impact discussed in the paper, which can be explored in future research.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Input data are available with Python software on Github.

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