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Mass customized/personalized manufacturing in Industry 4.0 and blockchain: Research challenges, main problems, and the design of an information architecture

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Abstract

Mass customized and mass personalized production has become facilitated by the fourth industrial revolution. The resulting industrial environments require the development of information systems able to take the specifications of customers and convey them to the production system in such a way as to contribute to the coordination of all the stakeholders and activities required to fulfill the orders of the customers. This is beyond the capabilities of traditional systems based on MRP and ERP, since the information should be managed in a flexible and decentralized way to exploit the Smart Manufacturing facilities of Industry 4.0. *Blockchain*, instead, is a technology that provides those features constituting a sound information supporting basis for mass customized/personalized production. Consequently, we explore the potential of blockchain as an information technology able to support industries that base their business models on mass customized/personalized production processes. This survey allows us to identify important challenges for further developments, highlighting three issues in the production setting: (i) to deepen the interoperability of systems,

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(ii) to generate more implementations, and (iii) to develop efficient consensus protocols. As a response to these insights we provide a conceptual design of how *blockchain* contributes to managing efficiently mass customized production systems. In our design the information of customer specifications can be fused with data from the production process to generate a plan to fulfill the demand. This design arises as a solution approach to three stated problem, which are faced by mass customized production systems.

Keywords: Mass Customization/Personalization, Manufacturing, Industry 4.0, Blockchain technology, Supply Chain, Information Systems

1. Introduction

The last years have witnessed the emergence of a fourth industrial revolution, known as Industry 4.0 (Assaqty et al., 2020). It involves a paradigm change in the conception of production systems, by incorporating connectivity and intelligence into all the levels of industrial control (Porter and Heppelmann, 2015; Yao and Lin, 2016; Aloqaily et al., 2018; Kotb et al., 2019; Yao et al., 2019). These capacities are mainly supported by the use of Cyber-Physical Systems (CPS) and the Internet of Things (IoT) (Xu et al., 2018; Fragapane et al., 2020). A Cyber-Physical system integrates the production processes performed in the real world with data processing procedures running in virtual environments (Yao and Lin, 2016). Thanks to their access to data generated by the physical processes of production, CPS are able to run procedures that conceptualize and yield useful analytic information about them (Lee et al., 2015). In turn, IoT transmits that information in real-time over a net of interconnected components, giving rise to what is known as a *smart factory* (Pereira and Romero, 2017). A distinctive feature of smart factories is their flexibility in the face of highly demanding or changing scenarios. They support new business models based on personalized production, offering customized products adapted to the preferences of individual customers. Some applications are found in important areas such as energy, health, transportation, agriculture, automation, and healthcare (Rathore et al., 2020; Xu et al., 2018).

One of the main impacts of this new paradigm has been the adoption of additive manufacturing technologies, because of their flexibility in adapting to the requests of new product designs (Arbabian and Wagner, 2020). The downside of this is that personalized production cannot be attained with standarized physical and computer procedures since both the products and the production processes arise from the specifications given by the customers (Kumar, 2007; Yao and Lin, 2016; Rossit et al., 2019b). Traditional modes of production, in which the products and the roadmaps for the operations and processes to be carried out for their production were previously established, are no longer tenable. But this poses the following question:

- *How should production processes for mass customized/personalized be designed and managed in Industry 4.0 manufacturing systems?*

A key aspect in the search for an answer to this question is the way in which information can be managed in the supply chain, up from the only concrete starting point, namely the specifications submitted by the customers. The system has to generate a prototype of the product and at the same time design its production process satisfying the supply chain requirements. After that, it becomes possible to schedule the production and finally start the execution of the plan (Kumar, 2007). This whole sequence provides a logical framework for the transition of the initial input given by the customer to the product to be delivered to her. Notice that while the initial input is given by the customers, who may upload them through digital platforms, other relevant pieces of information are provided by the databases associated to Industry 4.0 technologies (Dolgui et al., 2020). They can provide historical data as well as analytical insights that help improve the whole process. The system has to be able to keep track of the contributions of those different sources of information, including the data provided by the physical devices that may participate in the production process as well as by the supply chain stakeholders. *Blockchain* is an information system able to do this. It is, essentially, a data structure stored in a chain of linked blocks, in which the access to previous blocks or the addition of new ones requires a decentralized and distributed process of validation (Akter et al., 2020; Wang et al., 2021). The different participants in a personalized production can contribute their information in blocks, registering their contribution in a verifiable and permanent way (Iansiti and Lakhani, 2017; Tseng et al., 2020). Since no coordinating authority is needed to add those blocks to the chain, the participants in a smart factory can do so only by passing a required test of validity based on the consensus of the majority (Aloqaily et al., 2020; Frizzo-Barker et al., 2020; Meng et al., 2021). This main features of blockchain, namely the veracity of transactions, constitute perfect matches for the flexibility of the production process (Yli-Huumo et al., 2016). Besides, the blockchain records the roadmap for the entire supply chain and the production process, allowing each participant to check all the aspects already registered and assigned, to focus only on possible new contributions, avoiding the risk of duplicating efforts.

In this article we explore the potential of blockchain as an information technology able to support industries that base their business models on mass customized/personalized production processes. Since blockchain has been widely discussed in the literature as a solution for very diverse problems and contexts it is important to review the current state of the discussion on this technology, in particular with respect to its application in production systems considering the whole supply chain. In order to cover this aspect we ran an exhaustive review of the literature to find all the contributions relating blockchain with production or manufacturing, as well as with activities closely related to production, in its associated supply chain of goods and services. This review of the literature allowed us to detect the main breakthroughs in the field and to identify open challenges for future developments. In the light of these findings, we formalized the problems that may arise in a mass customized/personalized production system and developed a conceptual design for their solution using blockchain in Industry 4.0 environments.

2. Background: Advanced technologies in manufacturing settings

In this section, we review the advanced technologies in the manufacturing setting that have lead to a paradigm change in the way in which production is carried out, allowing the extension of traditional business models to the new mass customization/personalized production environments.

2.1. The Industry 4.0 environment

The industrial sector has experienced four main industrial revolutions in the last two and a half centuries. The first one was triggered by the introduction of steam power and power looms. Assembly line characterized the second industrial revolution while the adoption of mechanical automation, which came along in the 1970s, represented the third one. The latest revolution, the fourth industrial revolution, has been identified with the incorporation of smart manufacturing technologies, which integrate the use of CPS, cloud computing, artificial intelligence, and data science (Assaqty et al., 2020).

In smart manufacturing, the data collected by production machines is fed into physical control units by a SCADA (Supervisory Control and Data Acquisition) or similar device. This information can be transmitted to processing centers, providing Decision Support Systems with data traditionally restricted to control levels (Wang et al., 2015; Rossit et al., 2019b). That is, data usually collected through a Wireless Sensor Network (WSN) gets compiled by IoT, yielding a better picture of the state of the system. Notice that manufacturing generates large volumes of data in the supply chain, which require, in turn, of large data processing facilities (Moktadir et al., 2019; Zhong et al., 2016; Rossit et al., 2019a). Thus, the knowledge of the state of the whole system gets even more precise if there exists a connection with Cloud Computing centers (Al-Rahayfeh et al., 2018), increasing considerable the data processing capacities in the production environment (Tavana et al., 2018) but also increasing the possibilities of being cyber-attacked (Bahşi et al., 2018).

An interesting aspect of the penetration of Internet into Industry 4.0 systems is that it goes beyond its use in production flow processes. The Research and Innovation Funding Program for 2007-2013 (FP7) of the EU established that a future networked society had to be grounded on four feet: Internet by and for People (IoP), Internet of Contents and Knowledge (IoCK), Internet of Things (IoT) and Internet of Services (IoS) (Yao et al., 2019). IoP connects all the participants, eliminating the barriers between producers and consumers, creating online communities for the design, creation and sale of products. IoCK transforms data into information/knowledge that can be used in manufacturing systems (Yao and Lin, 2016). IoT links cyber and physical systems making fabrication processes intelligent. Finally, IoS uses the internet as a medium for the exchange of services by applying technologies like Service Oriented Architectures (SOA) or Cloud Computing (Aloqaily et al., 2018; Kotb et al., 2019). While all these Internet applications are currently in use, they will become faster and cheaper in the future, facilitating closer interactions between customers and production units, connected through platforms (Porter and Heppelmann, 2015).

2.2. Blockchain technology

Blockchain technology can be seen as a data structure where the information is grouped in blocks, which are chained and secured through cryptographic methods. Each block contains a cryptographic hash of the previous blocks in the chain, as well as a time stamp and the data on some transactions (Aloqaily et al., 2020). Blockchain is "an open, distributed ledger that can record transactions between two parties efficiently and in a verifiable and permanent way" (Iansiti and Lakhani, 2017; Tseng et al., 2020). Being a distributed ledger, blockchain is handled in peer-to-peer networks, adhering to a collective protocol for the communication among nodes and validation of new blocks (Hughes et al., 2019). Once recorded, the data in a block cannot be modified without altering the next blocks in the chain. Such alteration would require the consensus of most of the users of the network. The most popular application of blockchain is Bitcoin (Koutmos, 2019), a peer-to-peer version of electronic money, facilitating online transactions without requiring the intervention of financial institutions. Bitcoin highlights one of the main features of blockchain, namely the veracity of transactions, based on the consensus of the majority without requiring the intervention of third party acting as an authority (Frizzo-Barker et al., 2020; Yli-Huumo et al., 2016). However, the application of the blockchain technology is not limited to financial markets and can disrupt any centralized or regulated system that coordinates valuable information (Upadhyay, 2020; Butt et al., 2019).

There are five main features that identify in this technology (Iansiti and Lakhani, 2017). The first one is that it is a distributed database in which all the users have access in the same footing. Each user can verify the transactions made by any other user without going through intermediaries. The second feature is the peer-to-peer linkage between users, again without regulators or intermediaries. The third feature is the transparency of the system since, as said, each transaction and its associated value is visible for anyone with access to the system. Each user has an identification address and each of them can decide to remain anonymous or reveal her identity, but in the transactions only matter the addresses. The fourth feature is the irreversibility of records. Once a transaction is recorded and all the hash values are updated, the record cannot be modified because this would affect all the other blocks in the chain. The fifth feature is the digital nature of the ledger, which allows the use of algorithms and computer procedures to carry out automatically any transaction.

There are different possible procedures for validating the incorporation of a block in the chain. Bitcoin, for instance, uses proof-of-work (PoW), in which each user can only validate a block by solving complicated puzzles, requiring a heavy computation load and thus very demanding in electrical power (Swan, 2015). This protects the system of cyberattacks, which the openness and deregulation of the system seems, in principle, prone to incentivize. Another validation procedure is by proof-of-stake (PoS), which, unlike PoW, bases the validation on the capacity or willingness to do heavy work. It validates the blocks by users that have more valid transactions, being the effort to be carried out inversely proportional to PoW. The assumption behind PoS is that those who have more at stake (i.e. more transactions registered) are particularly interested in the survival of the system and thus are more willing to shield it from attacks. PoS requires much less computation (and electrical power), optimizing the use of resources.

Since blockchain and its inherent combination of consensus algorithms, distributed data storage, and secure protocols can be used to build robustness and reliability into CPS systems (Rathore et al., 2020), we will argue for its usefulness in handling the demands in mass customization/personalized production systems in Industry 4.0 environments, contributing to generate valid production plans in an autonomous and decentralized way.

3. Literature review

We conducted a literature review to find the contributions relating blockchain with production or manufacturing, as well as with all the activities closely related to production, in its associated supply chain of goods and services. Thus, we focus, in particular, on the references to manufacturing processes in the supply chain context as to assess the novelty of our proposal. This review follows the methodology proposed in (Chen et al., 2017), including four steps: (i) data collection, (ii) descriptive analysis, (iii) categorization analysis and data evaluation, and (iv) interpretation.

3.1. Data collection

This process follows the review methodology suggested by Andriolo et al. (2014), including the restrictions on language, temporality, database reviewed, and the selection of keywords for the search. Accordingly, we looked up research articles written in English and published until January 11, 2021, and reported in the Web of Science (WoS) database, considered the world's leading scientific citation search and analytical information platform (?). Specifically, we searched for the contributions that relate blockchain with production or manufacturing, as well as with all the activities closely associated to production, like those in the supply chain of goods and services. We selected relevant keywords classified into three major groups:

- Keywords related to blockchain: Blockchain, Smart Contract.
- Keywords related to manufacturing processes: Production, Manufacturing.
- Keywords related to supply chain: Supply Chain.

The search of the WoS database sought to find articles containing at least one keyword from each group, yielding 93 articles.

3.2. Descriptive analysis

To test the relevance of the collected articles, we analyzed the titles and abstracts. The research articles excluded were those that did not involve an in-depth consideration of blockchain. This means that a research article that only mentions blockchain as a digital technology but does not describe its advantages and disadvantages, or does not discuss its properties or does not present an application will be excluded from our analysis. Consequently, we validated a total of 67 research articles to be subject to a descriptive analysis, including the time of publication, the recognition of the journal of publication, an analysis of the structure of co-authorship, and a study of the keywords used.

3.2.1. Time of publication

The first research article selected was published in 2017 (Kennedy et al., 2017), reflecting that this research area has only recently attracted interest since our search of the database did not asked for a lower temporal boundary. Furthermore, as shown in Figure 1, once the research area attracted interest, the number of research articles related to blockchain has increased exponentially.

3.2.2. Journal recognition

For this analysis, a significant factor is the incidence of journals in the research topic. A total of 51 journals published the selected research articles.

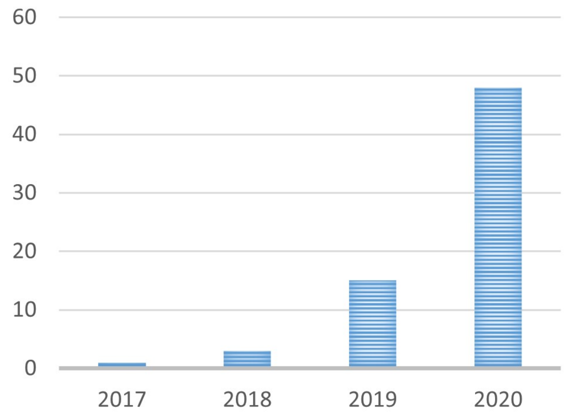

Figure 1: Distribution of research articles over time

Several of these journals have published only one research article from the selected class, indicating that there seem to not exist *specific* journals for this research topic. In this context, Figure 2 presents the journals that have published two or more research articles in our list. **IEEE ACCESS** stands out with seven publications, representing 10.4% of the total, while the **INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH** published 7.5% of the selected research articles.

Although 51 journals have published the research articles in this study, there are only 29 WoS search categories corresponding to them. The main search categories are *Computer Science*, with 13 research articles (19.4%), followed by *Computer Science; Engineering; Telecommunications*, with eight research articles (11.94%). Next comes *Business & Economics*, including seven research articles (10.45%) and, finally, *Engineering; Operations Research & Management Science* with six research articles (8.96%), as indicated in Figure 3.

3.2.3. Co-author analysis

The co-authorship analysis seeks to determine the main authors on this research topic and detect the existence of work teams if possible. Figure 4

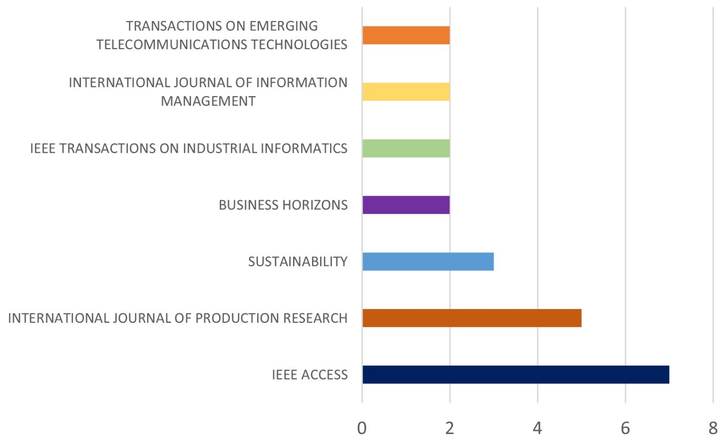

Figure 2: The leading journals that publish the research articles.

shows the relationships among the 229 co-authors of the published 67 research articles, where the edges represent the relationships among the authors and the size of a node represents the amount of research articles published by the corresponding author. On the left panel of Figure 4, 56 clusters represent the groups of authors that published one research article each. Meanwhile, each of the four groups of authors on the right panel have published more than one research article. As it can be noted, most of the co-authors have published only one research article on the research topic. However, some researchers stand out, for example, in the blue cluster at the right panel of Figure 4, Raja Jayaraman and Khaled Salah have published four research articles together (Debe et al., 2020; Alkhader et al., 2020; Hasan et al., 2020; Salah et al., 2019) while Junaid Arshad (Debe et al., 2020; Alkhader et al., 2020) and Mohammed Omar (Hasan et al., 2020; Salah et al., 2019) have co-authored two of these research articles. Furthermore, Neeraj Kumar, in the violet cluster at the right side of Figure 4, has two co-authors groups (Bodkhe et al., 2020; Sharma et al., 2019), just like Malin Song, in the light blue cluster, (Zhu et al., 2020; Pan et al., 2020), and Stephan Wagner, at the orange cluster, (Manupati et al., 2020; Kurpjuweit et al., 2021).

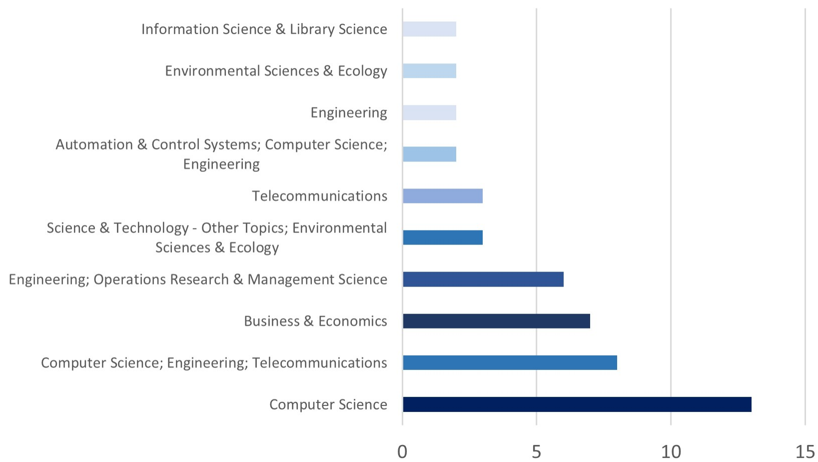

Figure 3: The leading Web Of Science search categories that integrates the research articles.

3.2.4. Keywords

This keywords analysis allows us to graphically understand the main applications of blockchain. Figure 5 shows all the keywords of the selected research articles, and the size of each word or concept represents the number of times it appears among the 67 articles. *Blockchain* is the most repeated word, followed by *supply chain*. Besides, some blockchain characteristics are highlighted, including *traceability*, *smart contracts*, *distributed ledger technology*, *security*, and *trust*. Also, blockchain applications are noticeable, like *food safety*, *food trading*, *additive manufacturing*, *3D printing*, *medicine*, *healthcare*, *finance*, and *energy*.

3.3. Categorization analysis

Even tough the search question focused on manufacturing and supply chain, we also found other general contributions related to blockchain, only a few of which are real world case studies of the use of blockchain. The novelty of this technology is evidenced by the fact that literature reviews arose in our search. The papers we found can be classified as follows:

- *Potential applications in manufacturing*: it seeks to understand how the manufacturing process can integrate blockchain, that is, how the informa-

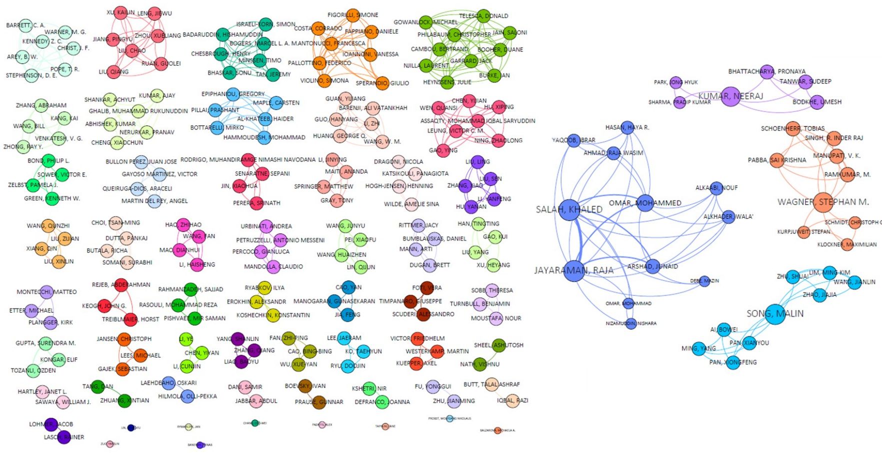

Figure 4: Co-authorship network.

tion it encodes can be used by the production process itself. The most iconic example is its use in Additive Manufacturing (AM). In this category we include only contributions related to the manufacturing stage.

- *Potential applications in the supply chain*: it intends to see how supply chains may use blockchain, that is, the ledger of information from outside the company, for example of suppliers, retailers, clients, etc. We consider here research articles assessing simultaneously several stages of the supply chain, like supply, transport, production and sales, among others.

- *Potential applications in general*: even though *supply chain* was one the main keywords, we are interested in detecting research articles in other interesting areas.

- *Field studies, interviews, or business applications*: we want to detect the research articles that present applied or real case studies of the use of blockchain. Notice that contributions on this research topic are quite recent.

- *Literature review*: it seeks to distinguish literature reviews or analysis frameworks developed to present broad pictures of blockchain and its ap-

Figure 5: Keywords study by the number of times it appears in the research articles assessed.

plication to certain areas.

Table 1 shows the results of this categorization and Figure 6 depicts it. We highlight the fact that most of the research articles correspond to *supply chain* (37), followed by *field studies* (16), while there are only 5 research articles on *applications in general*. In turn, the seven research articles in the intersection (Bullón Pérez et al., 2020; Cao et al., 2020; Violino et al., 2019; Kurpjuweit et al., 2021; Scuderi et al., 2019; Lin, 2019; Fu and Zhu, 2019) develop *field studies* of the integration of blockchain in *supply chains*. Besides, we found that Chang (2020) and Mandolla et al. (2019) develop a *field study* applied to blockchain integration in *manufacturing*. Finally, among the 10 research articles tagged as *literature reviews*, only Rejeb et al. (2019) focuses on the application of blockchain in *supply chain*. All these articles are discussed in detail in the next subsections, when we address the topics according to our classification.

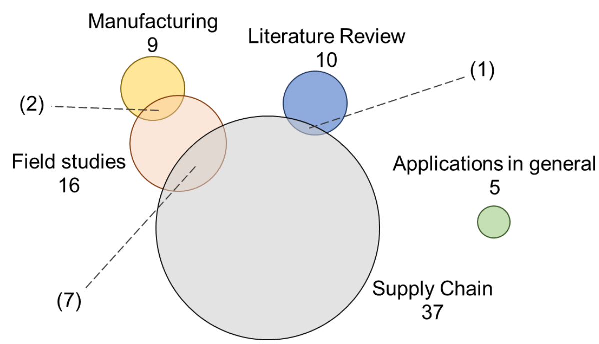

Figure 6: Number of publications by category. In parentheses, the number of articles corresponding to more than one category.

3.3.1. Manufacturing

On the integration of blockchain in manufacturing systems, three investigations focus on the incorporation of blockchain as a tool to track the exchange of products between different parties and production stages. In (Assaqty et al., 2020) the emphasis is on supporting real-time collaboration and integration in smart manufacturing while (Cambou et al., 2020) is concerned with the mitigation of man-in-the-middle attacks in *additive manufacturing* (AM) contexts. Finally, (Westerkamp et al., 2020) discusses blockchain as a way of enhancing security in manufacturing systems. Another investigation related to AM (Alkhader et al. (2020)) proposes blockchain to protect designs in AM industry while Mandolla et al. (2019) suggests the use of this technology to certify and monitor the whole production process of components. This last research describes how to integrate blockchain at each stage of AM, presenting a case study of the fabrication of an airplane parts. Besides, Kennedy et al. (2017) seeks to ensure the authenticity and quality of the parts produced with AM, using chemical signature and blockchain registration. They use Ethereum to implement their proposal, generating a proof of concept showing that it reduces the transaction costs.

In relation to information systems management in manufacturing, Chang (2020) seeks to exploit the information stored in a blockchain at the Datong Shoes and

Materials Company (Taiwan) to select a collaborative technology. Meanwhile, Tozanlı et al. (2020) uses the information recorded in a blockchain, namely data on the origin of a product, the invoice for the materials used in the production process, the remaining life time at the component level, as well as the assembly/disassembly instructions, to eliminate the uncertainty in production operations, boosting the transparency in the supply chain. Furthermore, Ko et al. (2018) develops a game where two manufacturing companies compete, one using blockchain, to estimate the costs of not implementing a blockchain, like those of hiring external audits.

3.3.2. Supply Chain

Among the 37 research articles that refer to the integration of blockchain in supply chains, around 65% of them state that blockchain could connect the supply chain entities, improving the transparency, coordination, and traceability of their interactions. However, these investigations lack any descriptive details on how to implement these technologies in production plans in mass customized/personalized production systems.

In turn, nine research articles focus on the incorporation of blockchain, mainly to track different actions along the entire supply chain, describing database architectures, the designing step of smart contracts and the integration with other technologies. For example, Debe et al. (2020) proposes a prototype of a management architecture able to track the commercial flow of drugs. Sharma et al. (2019) proposes a blockchain-based distributed framework simulated on the Ethereum platform for the automotive industry, in order to track the lifecycle of a product in a supply chain, starting with the raw materials and the manufacturing activities up to the maintenance and recycling phases. Furthermore, Mao et al. (2018), Fan et al. (2020), Gao et al. (2020), and Salah et al. (2019) integrate blockchain to food supply chains to strengthen the effectiveness of supervision and management by tracing the origin and the use of raw materials, recording transactions to enhance their efficiency and safety with high integrity, reliability, and security. Besides, Kumar et al. (2020) develops a platform to secure Cloud-Based Manufacturing operations based on private blockchains; meanwhile, Zelbst et al. (2019) explores the integration of blockchain with RFID and IIoT in manufacturing systems to enhance transparency along the supply chain; finally, Cao et al. (2020) designs a new traceability system using blockchain-based IIoT mechanisms for the steel industry.

In addition, four research articles propose uses for blockchain in supply chains other than as a mechanism to track activities. So, Epiphaniou et al. (2020) develops a platform for the coordination of supply chain information, Rahmanzadeh et al. (2020) presents a plan for making tactical supply chain decisions and proposes a registration mechanism in which the ideas and creative works are collected and refined, Li et al. (2020a) develops a model for the selection of suppliers based on a blockchain platform, and Manupati et al. (2020) develops a distributed ledger-based blockchain approach for monitoring the performance of supply chains and optimizing at the same time both emission levels and operational costs.

The fact that the number of these research articles is small indicates that blockchain and its applications in supply chain and logistics are still in their infancy. This also poses the need for application-oriented studies that may contribute to expand the understanding of the outreach of this technology.

3.3.3. Applications in general

Among the investigations that were not related to manufacturing or supply chain, Bodkhe et al. (2020) assess the usefulness of blockchain to protect the stakeholders in precision irrigation systems; Zhu et al. (2020) discusses the possible use of blockchain to energy efficiency; Tappuni (2020) describes some possible uses in the publishing industry; Pazaitis (2020) states that established firms face significant challenges deploying the coordination patterns of open innovation communities; and Liu et al. (2020) propose a novel integrated multi-attribute group decision-making method to help enterprises estimate the appropriateness of blockchain vendors by taking into account a comprehensive list of influence factors.

3.3.4. Field studies

The field studies found in the selected group of articles can be divided into, on one hand, those focusing on interviews or surveys about the potential of incorporating blockchain applications in firms and, on the other, on those that concentrate on the consequences of effectively implementing blockchain applications.

With respect to the potential of incorporating blockchain applications in firms, Pan et al. (2020) review blockchain applications in 50 Chinese companies, concluding that the expansion of the assets of the firms are a significant driving factor for the implementation of blockchain technology. Meanwhile, Lohmer and Lasch (2020) run interviews with ten experts in Europe, identifying the potential for new collaborative manufacturing networks and efficiency gains through the use of smart contracts linking IoT and blockchain. Among the barriers to the implementation of blockchains, the experts were in general skeptic with respect to the trust and transparency in networks, due to missing standards, unclear governance systems, and to regulatory and legal uncertainties. Likewise, Kurpjuweit et al. (2021) assessed the barriers to the implementation of blockchain in AM with 12 experts, professionals or academics, concluding that the main barriers consists in the absence of blockchain-skilled specialists on the labor market, missing governance mechanisms, and a lack of firm-internal technical expertise. On the positive side, blockchain-based AM platforms are expected to enhance the visibility of the supply chain, drive its digitalization, support its financing, and contribute to the emergence of shared factory systems. Similarly, Lähdeaho and Hilmola (2020) revealed that professionals and experts from Finnish and Russian logistics firms perceive blockchain as a still immature technology and that these companies are not well prepared for the new environmental demands on logistics. Furthermore, Lin (2019) argued that blockchain is not able to solve all the governance issues in the food chain. Rather, it may pose regulatory questions about the technical capacity and the infrastructure gap, the scalability and the implementation costs, as well as on global standardization politics, cybersecurity and data protection, as well as about the inherent technologically limits of blockchain. In addition, the experts pointed out that policy challenges to both developed and developing countries in terms of operational expertise and technical infrastructure and power asymmetry in international standard-setting cannot be ignored. Meanwhile, Hartley and Sawaya (2019) discuss considerations arising in 14 large, mature service and manufacturing companies, observing that none of the companies has specific plans to adopt blockchain in the foreseeable future. This is either because they are waiting to see how blockchain might fit their needs and how others adopt the technology, or because they think that other technologies can be used to encrypted private networks, delivering the same functionality. Thus, it seems that currently the perceived value of blockchain for supply chain is limited to specific cases that have a high need for increased visibility or when there exist complex document flows among the different actors in the supply chain.

In terms of the consequences due to the effective implementation of blockchain applications, Sheel and Nath (2019) collected data from 397 supply chain practitioners in India to conclude that blockchain technology can improve the adaptability, alignment, and agility of supply chains, leading to competitive advantages and improved firm performances. Bullón Pérez et al. (2020) present a study on the fabrication of shirts, in which the details about time and place of elaboration, the origin of raw materials, the quality of materials and information about the workers ensure the transparency of the supply chain, the authenticity of clothes, the reliability, integrity, and validity of the retail final products, and of the elements that compose the whole supply chain. Furthermore, Fu and Zhu (2019) apply blockchain to manage the endogenous risk of the supply chain due to the information asymmetry in the medicine industry, concluding that the application of intelligent contract operation mechanism under a consensus authentication of the blockchain can influence the performance of big production enterprises in terms of the response speed, supply accuracy, integrity of cooperation, cost of business interactions, supply quality, and supply price. Besides, Cao et al. (2020) designs a traceability system incorporating the production and distribution firms, as well as the product users and the quality regulators, to promote the transformation and upgrade of the steel industry. Furthermore, Scuderi et al. (2019) and Chen et al. (2020) state that blockchain can play a leading role in the democratization of the supply process since it can solve problems such as asymmetric information, unreliable third-party institutions, and poor traceability in agricultural systems. Along the same line, Bumblauskas et al. (2020) present an implementation of a blockchain in the production and supply chain of a delivery system of eggs from a farm to consumers, facilitating the accurate and transparent movement of these goods through global supply chains. Then, Violino et al. (2019) develop a questionnaire for 1120 consumers and three producers of Italian extra virgin olive oil, asking for the consumer preferences about a system with a blockchain-based tracing platform.

3.3.5. Literature Review

As presented in Figure 6, ten research articles correspond to literature reviews, which were all published in 2020. Among these research articles, only one presents a bibliographic review jointly with a discussion of the potential applications of blockchain to supply chains. The other nine present only bibliographic reviews. Rejeb et al. (2019) point out that blockchain technology in combination with IoT may enhance the transparency in the value chain, increase *Business-to-business* (B2B) trust and increase the effectiveness and efficiency of modern supply chains. In addition, it presents six research propositions outlining how blockchain technology can impact features of the IoT such as scalability, security, immutability, auditing, traceability, interoperability, and quality.

With respect to the other nine research articles, Dutta et al. (2020) reviewed 178 articles from the Scopus database evaluating applications, integration, and implementation of the blockchain technology in supply chain and logistics, examining industrial sectors such as aviation, finance, the automotive industry, technology, and education. They conclude that the integration of blockchain could transform the structure of the supply chain by ensuring the collaboration among all the actors involved. Sobb et al. (2020) assess how the information is processed and operated on military supply chains and its secure integration with new technologies, including blockchain, IoT, and CPS. Likewise, Erokhin et al. (2020) studied how the introduction of distributed ledger technology into the standard model of the supply chain can prevent the circulation of poor-quality pharmaceutical products thanks to the transparency, invariability, and distributed nature provided by blockchain, guaranteeing the compliance with rules of logistics and transportation in a pharmaceutical supply chain. These advantages reduce the risk of allowing a defective product to enter the market, increasing the effectiveness of its detection. Furthermore, Rodrigo et al. (2020) present a literature review, validated with interviews, on the potential application of blockchain to the estimation of carbon emissions in construction supply chains, although it does not provide any information about the interviewees.

In addition, Zuo (2020) defines blockchain and discusses its application areas, including a description of smart contracts and a proposition of a three-layer blockchain reference architecture for smart manufacturing in the context of AM, focusing on the interconnected machines in a smart factory to autonomously exchanging information and controlling each other. Meanwhile, Balzarova (2020) presents a conceptual review of possible approaches that can be adopted in commerce, predicting that blockchain is a possible technology to be applied to implement ecolabels. Kshetri and DeFranco (2020) survey the applications of blockchain in the developed and developing countries to track the origins and storage of food and beverages, whereas Leng et al. (2020) survey 183 research articles concluding that the transparency and traceability provided by blockchain and smart contracts show promise for enhancing the sustainability of manufacturing networks. Finally, Rymarczyk (2020) presents a survey on Industry 4.0 technologies, including blockchain but without discussing possible implementations.

4. Discussion of the reviewed contributions and identification of research gaps

In this section we analyze the most significant contributions reviewed in the previous section and classify the main themes covered by them. We also identify the main topics that could be deepened in future investigations. Finally, in the light of gaps we have found in the literature we will discuss the potential and the advantages of using in blockchain in mass customized/personalized manufacturing.

4.1. Review results

Manufacturing:. the main variant of industrial production to which blockchain has been applied is *additive manufacturing*. Blockchain has been very efficient to managing the files of customer specifications as well as those of production designs. This is relevant, since one of the usual problems in mass customized/personalized production is how to manage the information since each production order is different from another. Nevertheless, since very few contributions in the literature address this question, we can infer that the topic is still at a very early stage of investigation.

Supply chain:. in this field we found the largest amount of contributions in the blockchain literature. They emphasize on the support provided by blockchain to the dynamical and transparent use of information in supply chains. This is so because each node in a supply chain may hold a copy of the ledger, but without being able to modify it unilaterally. A remarkable application discussed in this literature is the successful use of Ethereum as the basis for the evaluation of different configuration of supply chains (Salah et al., 2019). A particular niche application of blockchain is in the supply chain of food industries, in which it allows to trace the origin and the uses of raw materials (Mao et al., 2018).

Considerations about the adoption of blockchain:. there exist a wide dispersion in the topics studied under the rubric "applications of blockchain in industrial contexts". This literature is particularly relevant in disclosing the views held by managers about the potential of incorporating blockchain applications in their firms. Most of them point out that one limitation for its widespread adoption is the lack of trained personnel able to work with this technology (Kurpjuweit et al., 2021). In many cases, managers considers that blockchain is still at an early stage of development and thus not yet ready to be adopted (Lähdeaho and Hilmola, 2020). Despite this, field studies have shown that customers who confirm that blockchain is able to convey reliable information about the provenance of food are willing to pay an extra price for the use of this technology (Violino et al., 2019). This indicates that blockchain contributes to the creation of value. This is also revealed by a number of studies on the adoption of this technology by industrial firms that confirm the existence of gains from its ability to administrate information.

Literature reviews:. while several reviews of the literature on blockchain have been published, none of them addresses exactly the problem in manufacturing contexts as covered in this paper. Most of those reviews focus on blockchain in supply chains while others refer to its impact on manufacturing systems. A common conclusion reached in those reviews is that the main contribution of blockchain resides in its transparency and its ability to integrate different links in supply chains, providing more flexibility and resilience to their associated systems.

4.2. Research gaps: future research lines

Currently, the main advantage of blockchain in manufacturing ensues from its capacity to handle and integrate diverse sources of information. In what follows we discuss some prospective lines for further research about other benefits of this technology.

Interoperability:. a highly relevant factor in the integration of different devices in a shop-floor is their *interoperability*, which allows them to communicate with each other, even if they come from different manufacturers. Then, the full usability of blockchain in this setting depends on the interoperability of all the devices, that must be able to record valid transactions in the ledger, readable by the rest of them. This, in turn, requires the design of new protocols and data structures able to support the access and validation of blocks by all the components of a manufacturing system.

Study cases:. this is an area that requires much more investigation. While some concrete applications have already been discussed in the literature, more instances of the application of blockchain are needed to assess the understanding of its possibilities and eventual limitations. Some questions are still open about practical issues. For instance, since production processes frequently generate intermediate components for their "consumption" in the fabrication of larger ones, the full traceability of the different parts of a product needs to take into account these nested operations. In this sense, Westerkamp et al. (2020) present an interesting comparison between physical products and consumable digital tokens. This could open the possibility of producing lots with only a few units involved in the production process, facilitating the manufacture of personalized goods.

Consensus mechanisms:. the existence of consensual agreements are fundamental for the application of blockchain, since they allow the decentralization of the system. Currently the most popular mechanism for reaching consensus is *Proof-of-Work* (PoW), in which each user can only validate a block by solving complicated puzzles, requiring a heavy computation load and thus being very demanding in electrical power (Swan, 2015). While it works well in the case of open networks, as in the case of Bitcoin, it is highly inefficient, demanding large amounts of energy. Thus, developing better consensus protocols should become a very active research topic. In the case of manufacturing, these protocols should be oriented towards their use in private networks, since in rare cases an industry allows access to sensitive information about its processes to the public (and actual or potential rivals). The privacy of this internal network allows the implementation of mechanisms based on *Proof-of-Stake* (PoS) procedures, allowing a more efficient use of resources and time. This validation procedure, unlike PoW, is based on the idea that those who have more at stake (i.e. more transactions registered) are particularly interested in the survival of the system and thus are more willing to shield it from attacks. PoS requires much less computation (and electrical power), optimizing the use of resources.

4.3. Blockchain in mass customized/personalized manufacturing

Our investigation is focused on the blockchain use in mass customized/personalized manufacturing. The literature on this subject is quite recent, indicating that it is still in its infancy. But it already indicates that blockchain has the potential to solve one of the main problems in personalized manufacturing, namely to overcome the tendency to resort to information management methods used in standard mass production. This is because in customized/personalized manufacturing, both the good *and* the production process have to be personalized, and this is why classical management paradigms like MRP (Material Requirements Planning) and ERP (Enterprise Resource Planning) are no longer tenable in this setting.

In classical production settings MRP and ERP are justified by the standardization of the processes corresponding to any given production order. This allows to estimate the production capacities, times, resources, costs, etc., associated to fulfilling the received orders. But in personalized manufacturing, there is no direct association between the order made by a customer and the databases of MRP and ERP. Blockchain, instead, exploits the possibilities of smart production systems and their associated computing facilities. In most of the contributions to the literature on blockchain in manufacturing the focus is on *Additive Manufacturing* which currently fills out the market niche for personalized products.

5. Statement of the problems in a mass customized/personalized production environment

Based on the review of the literature and the features of blockchain, in this section we propose a line of research associated with mass customized/personalized production environment, in which blockchain allows to enhance planning and decision-making structures.

Industry 4.0 technologies have greatly enhanced the ability to customize products to better suit customer needs and requirements. These improvements are due to the fact that Industry 4.0 incorporates a growing level of autonomy, together with the necessary computational capabilities, at the lowest levels of the production control structure (including the shop-floor). This gain in autonomy, allows to have a more agile and flexible manufacturing system. It is in this sense that the concepts of Cyber-Physical Production Systems (CPPS) arise, in which it is proposed that the entire production control structure (for example ISA-95) will be controlled by the CPSs (Monostori, 2014), and through IoT, the CPS will communicate with each other, where each CPS will try to optimize its own performance and will coordinate the different stages of production and the whole supply chain with other CPS. However, this heterarchical vision of production planning (without any hierarchy within the system), may not lead to the resulting planning being completely efficient. Since, it is possible that where a set of agents optimize their own operation, global efficiency will not be achieved.

In contrast, system designs have emerged in which a *semi-heteracchic* design is proposed (Grassi et al., 2020a). Semi-heterarchical systems are an intermediate point between hierarchical and heterarchical systems, where there is a set of constituent elements that have autonomy, but in certain types of actions these elements are subordinate to systems that are higher in the hierarchy. Recently, these structures have been shown to exploit in a more successful way the advantages proposed by the first Industry 4.0 designs a few years ago (Gonzalez et al., 2019; Grassi et al., 2020b). However, an important issue that these structures must ensure is the ability to manage the information within the system, and that this information is updated and does not generate duplication of records or orders. That is why we propose a design based on blockchain technologies, solving the production planning for mass customized/personalized products in its supply chain context in cases where the manufacturing system follows a semi-heterarchical structure.

In formal terms, we consider a class $\mathcal{I}$ of customers and a firm in a given manufacturing sector. Let $\mathcal{J}$ be the class of products that can be demanded by individuals in $\mathcal{I}$. By $\mathcal{T}$ we denote the set of feasible prototypes that can be produced by the firm. Each costumer $i \in \mathcal{I}$ wants to acquire a new and specific product j_i, which i requests to the firm. Let $\mathcal{P}$ and $\mathcal{O}$ be the sets of processes and operations historically used by the firm and its supply chain stakeholders. Assume that it has a set of CPS $\mathcal{K}$ to handle the production of the new item. Each $k \in \mathcal{K}$ can perform a set of operations $\mathcal{O}_k$ and/or run a set of processes $\mathcal{P}_k$. All the information associated to the processes, operations and production resources (i.e., processing times, material procurement, machinery, and standards of quality, among others) is recorded in historical databases. In the context of this production system, we identify three main problems to be solved.

- **Main problem 1** Given a new product $j_i \in \mathcal{J}$ demanded by a customer $i \in \mathcal{I}$, identify a subset of processes $\mathcal{P}_{j_i} \subseteq \mathcal{P}$ and/or a subset of operations $\mathcal{O}_{j_i} \subseteq \mathcal{O}$, required to produce a prototype $t_{j_i} \subseteq \mathcal{T}$ for j_i according to the specifications of i.

- **Main problem 2**: Given a subset of prototypes $\mathcal{T}_\ell \subset \mathcal{T}$ and the processes and/or operations required to manufacture them, determine the class of expert cyber-physical systems (ECPS) $\mathcal{E}_\ell$ such that each $e \in \mathcal{E}_\ell$ is able to manufacture *all* the elements of $\mathcal{T}_\ell$ by coordinating the activities of a class of CPSs $\mathcal{K}_e \subset \mathcal{K}$, considering all the supply chain stakeholders. This subset of CPSs gives rise to an ECPS when its members have gained experience in running a family of processes and operations. This problem amounts to associate the activities involved in the feasible solutions to the *main problem 1* to a subset of CPSs experienced in carrying them out.

- **Main problem 3**: Assume as given the class of prototypes $\mathcal{T}_\ell \subset \mathcal{T}$ demanded by the customers, and the corresponding ECPSs $\mathcal{E}_\ell$. Consider the class of processes $\mathcal{P}_{j_i}$ and the set of operations $\mathcal{O}_{j_i}$ able to produce a given prototype $t_{j_i} \subseteq \mathcal{T}_\ell$ considering the requirements of all the supply chain stakeholders, according to the solutions to the *main problems 1* and *2*. We have to find a subset of ECPS $E_{j_i} \in \mathcal{E}_l$ able to fabricate the prototype t_{j_i}, according to a given *roadmap* for its production process.

The solution to these problems yields the optimal outcome in the three-stage decision-making model of a firm in a mass customized/personalized production environment depicted in Figure 7.

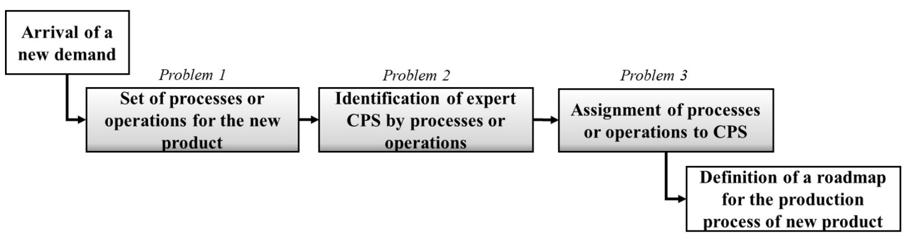

Figure 7: Production planning in a mass customized/personalized production environment

6. A blockchain solution

We characterize the output of each of the three main problems of the previous sections as follows:

- **Output of the main problem 1**: The output of this problem is the definition of the core processes and core operations to produce a prototype $t_{j_i} \in \mathcal{T}$ involving all the supply chain stakeholders. These processes and operations are drawn from the historical records of previous production experiences. This problem represents a *concept test* in the development of the new product demanded by the consumer. If the database of past experiences does not include enough processes and operations that might be needed to produce the prototype, the customer is informed that the requested product cannot be produced (at least by autonomous processes).

- **Output of the main problem 2**: The solution to this second problem yields the class of ECPS, the network of systems that are able to manufacture the set of prototypes $\mathcal{T}$ according to the specifications of the class of customers $\mathcal{I}$. Each ECPS executes the activities leading to the satisfaction of the demands of customer $i \in \mathcal{I}$. The production design so obtained is defined by the prototype t_{j_i}, the set of processes and operations required P_{j_i} and O_{j_i} and the resources $\mathcal{R}_{j_i}$ obtained from the supply chain stakeholders needed to fabricate it.

- **Output of the main problem 3**: The solution to this problem advances the analysis from production planning to production programming (defining a *roadmap*). Given the class $\mathcal{E}_l$ we have now to specify a subset E_{j_i} for each prototype t_{j_i}.

Sophisticated information systems are necessary to solve autonomously the problems presented in Section 5. These systems need to be endowed with the capacity to process the inputs of those problems and generate the required outputs. Previous studies have introduced system architectures incorporating some of those capacities, mostly seen as embodied in Digital Twin frameworks. So, for instance, (Roy et al., 2020) develops a Digital Twin for friction stir welding process while (Bao et al., 2019) proposes the use of a Digital Twin for the fabrication of aerospace structural components. And more general examples or descriptions of Digital Twin frameworks can be found in (Tao and Zhang, 2017).

Alternatively, the problems in Section 5 can be addressed by implementing Business Process Management (BPM) systems (Erasmus et al., 2020; Estruch and Álvaro, 2012), which establish a direct connection between production tasks and business functions. With respect to possible applications of the blockchain technology to solve similar problems, to the best of our knowledge the only work that addresses this is Zhang et al. (2020a), where a blockchain information system is associated to a IIoT (Industrial Internet of Things) architecture using Hyperledger Fabric. More precisely, the authors present a blockchain system to handle in a decentralized way the information and knowledge management facilities of an Intelligent Manufacturing System, showing that blockchain improves the resilience and security of the system by incorporating smart contracts and permission strategies. However, its focus is restricted to the manufacturing process without considering the supply chain stakeholders.

A step forward to the solution of the problems of Section 5, is the incorporation of customer interactions into the blockchain structure, in such a way that the entire customized production process becomes completely integrated in a secure and decentralized way. We propose a procedure, based on blockchain technology, incorporating the solutions to these three problems to generate automatically a *roadmap* for the production of a new product j_i demanded by customer i, as illustrated in Subsection 6.1. This procedure is intended to be implemented in Industry 4.0 environments, where many operations and processes can run autonomously using CPS (Monostori et al., 2016). In Figure 8 we illustrate how the different sources of information and the outputs of the main problems are associated. Notice that the sources and types of data associated to each one of the main problems differ. So, for instance, at the start of the process the relevant data are customer specifications and descriptions of the required operations and other features of the production processes while at the next stage the relevant information is historical data about related processes and operations. All the data types and the way in which they are processed become incorporated and consolidated into the blockchain scheme, as shown at the bottom of Figure 8.

For this we consider a semi-heterarchical system, with a High-Level controller (HLC) that manages and monitors the behavior of several CPSs, which interact which each other in an autonomous manner. The interaction between the HLC and the CPSs as well as the exchanges among the latter must be synchronized

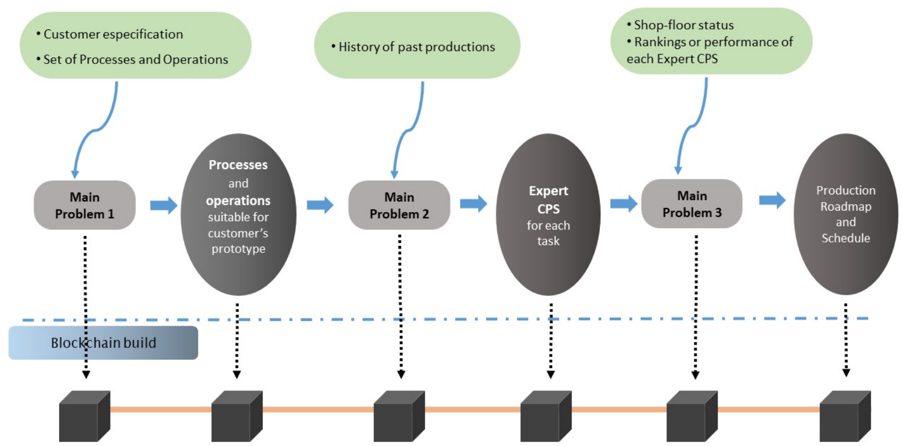

Figure 8: Main problems from mass customized production, information inputs and blockchain building

and organized. This is the stage at which we incorporate blockchain in our design as an information management system that provides the adequate structure for sharing information within decentralized systems.

To show how our proposed design works, let us see how it addresses our *Main problem 1*. Since it involves the translation of the request of product j_i by customer i into a class of operations and processes for its production and procurement. An autonomous solution obtains thanks to the ability of CPSs to go back and forth between the virtual and the physical realm (Lee et al., 2015). In a context of AM technologies, in which a 3D object is created by superimposing layers of material (Yampolskiy et al., 2018), advanced AM technologies can even help to create prototypes, improving the process of designing products (Arbabian and Wagner, 2020). Therefore, a full digital model of j_i can be obtained using the specifications provided by i and the 3D design tools available in Industry 4.0 systems, yielding a digital prototype t_{j_i}. This prototype can be analyzed by the production CPS using the database of the processes and operations previously executed ($\mathcal{P}$ and $\mathcal{O}$) and of the resulting products. By matching the specifications of t_{j_i} to the adequate subsets $P_{j_i} \subseteq \mathcal{P}$ and $O_{j_i} \subseteq \mathcal{O}$, we obtain the solution to the *main problem 1.* So, for instance, if the production of t_{j_i} requires hollow cylindrical shapes, the CPS in charge of lathes may identify the processes and operations corresponding to those shapes. Even when no subtracting operations and processes can be found matching the specifications of t_{j_i}, AM technologies can still be used, although the latter tend to be slower than the former (Arbabian and Wagner, 2020), and thus the first choice should always be to use previously applied processes and operations.

An important question is whether a conflict can arise among the different autonomous CPS in the selection of $\mathcal{P}_{j_i}$ and $\mathcal{O}_{j_i}$, since they can recommend different processes and operations, all of them satisfying the requirements of t_{j_i}. The worst case arises when those proposals are mutually exclusive, making it impossible to choose any one of them in a decentralized way. In our example, let us add to the recommendation of the lathe-controlling CPS one of the milling cutter CPS, suggesting to drill a hole and some additional operation. While both proposals may involve making a hole, they may differ on which should be the next operation. To let the autonomous system negotiate the recommendation to be followed can be complicated. An information system based on blockchain, instead, solves these kinds of conflicts easily. It also helps to address similar issue in the case of the *main problem 2.* This technology facilitates the decentralized organization and coordination of the contributions of the different CPS (the users of the blockchain network) to yield a roadmap for the production and the procurement of t_{j_i} , taking into account the supply chain stakeholders.

In order to achieve this goal, we will use the PoS validation method instead of PoW (Dolgui et al., 2020). New blocks of processes and operations will be validated by any CPS that is a better fit for a task than the others. This is less computationally demanding than the use of PoW. The fitness of a CPS for a given task is defined by the number of times that it has processed similar operations in the past.

6.1. An illustrative example

In order to give an illustration of our proposal, let us consider a company specialized in the fabrication of tennis rackets that receives a request for a personalized one, addressing the three main problems problems as depicted in Figure 9.

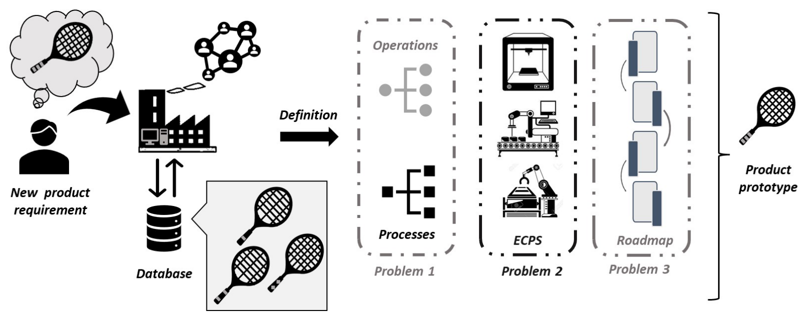

Figure 9: Representation of the three main problems in the decision-making process of a firm in a mass customized/personalized production environment.

The know-how of the firm in making this kind of sport equipment in the past can yield a family of rankings of the CPS, one for each possible task. Data analytic procedures can indicate which CPSs , machinery, suppliers, raw materials, transportation, among others have more chances to be selected and used at the different stages of the process based on certain criteria such as performance, price, quality, etc.. The blockchain protocol will give more weight in the validation of the recording of each new process or operation in the ledger, to the CPS with the highest rank in the corresponding stage. This means that even if the information is distributed and all CPS can make recommendations, the only contributions that will matter are those that are deemed fitter at each stage. Interestingly, a CPS with more chances of validating the activities at stage $s+1$ can revise those at stage s, already in the ledger. Changing them would be costly but this review allows it to recommend an adequate continuation to the process at $s+1$. This, in turn, contributes to the generation of a more efficient roadmap for t_{j_i}.

In this way, the CPSs will pick up the processes and operations that in the end yield the selected sets $\mathcal{P}_{j_i}$ and $\mathcal{O}_{j_i}$. Furthermore, since the blocks recorded in the ledger reflect the order in which they should be carried out, the entire ledger will become the roadmap for the production of t_{j_i}. Notice that, as already hinted, the implementation of the PoS validation also solves the *main problem 2* since it automatically identifies the CPSs that are fitter to the activities at each stage. That is, it yields the set E_{j_i} of ECPS for i's request.

6.2. Properties of the proposed blockchain solution

Let us analyze some important aspects of the *roadmap-as-blockchain* solution to the problem of handling the demands of customized/personalized production systems in Industry 4.0 environments.

- **Quality of the solution**: While the chain of blocks generates *one* roadmap, nothing ensures that it will be the optimal selection of sequence of processes, setups, procurement, etc. By design, each CPS recommends some operations for the production of t_{j_i}, oblivious of the possibilities of the next CPS in the sequence. On the other hand, the assignation of the relative weights at each step for the validation by PoS responds to the historical record. We can suspect that the resulting roadmap may constitute a good solution in the light of the material and product procurement and fabrication processes of the past, at the very least because it respects constraints like the idiosyncrasies of the firm or the layout of the system and, thus, belongs to the opportunity set of the global design problem.

- **Autonomy and speed of response**: One of the main virtues of this proposal is that the roadmap can be generated rather easily and efficiently. Since the entries in the ledger correspond to the CPSs that are fit at each stage, the response will be fast, without depending on the other units other than the previous one in the sequence. This induces an agile and flexible supply of customized goods.

- **User-friendliness**: Another aspect to highlight is that the ledger, so defined, will be readable by human users. Once the entire blockchain is validated, the ledger can be submitted to all the workstations without the need of further processing. In order to ensure this, the system should be implemented in an XML (Extended Markup Language). Then, both the autonomous CPSs and the human operatives can read it. An example of an XML that respects ISA 95 is B2MML (Business to Manufacturing Markup Language) (Harjunkoski, 2016). The use of such XML facilitates, in case of an unavoidable conflict during the generation of the ledger, the intervention of human users to make the decisions leading to the generation of an adequate roadmap of fabrication.

Finally, let us note that the blockchain approach does not provide a direct solution to the *main problem 3*, since it only responds to the question of how to design a production plan in an autonomous and distributed way. The *main problem 3*, instead, is that of programming the production activities. That is, assigning resources to processes and operations, defining start and due dates to the activities. This problem is basically that of scheduling the production process. Nevertheless, the ledger provides all the data required for scheduling the production process, as for instance the precedence relations between operations or their conditions of operation.

Furthermore, the database of past material and product procurement and production activities can be consulted to find, for all the CPSs that contribute to the ledger, the processing times and other relevant information of how they can ran their assigned activities. This provides relevant data for the design of the production schedule corresponding to the roadmap.

7. Conclusions

In this paper we reviewed the recent literature on the application of blockchain in manufacturing systems and the management of supply chains. This survey allows us to identify challenges for further developments such as (i) deepening the interoperability of systems, (ii) generating more implementations, and (iii) developing efficient consensus protocols. As a response to these insights we present a conceptual design of how blockchain may contribute to managing efficiently mass customized/personalized production systems. In our design the information of customer specifications can be fused with data from the material and product procurement and production process to generate a plan and coordinate the autonomous and decentralized system of CPSs to fulfill the demand. This design arises as a solution to three problems faced by mass customized production systems. It allows to delegate some aspects of the decision-making processes in production planning to the CPSs themselves. Since the proposal assumes a PoS validation procedure to avoid conflicts and the duplication of efforts among the CPSs in the network.

We leave the automatization of the solution to the third problem (that of assigning operations and resources in a time path) for further research. On the other hand, while our approach allows the solution of *problems 1* and *2*, we only can ensure the acceptability of the solution generated by the blockchain system. Ensuring its optimality in both the use of resources and the time schedule of production, is again a topic for future research.

Acknowledgements

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Table 1: Publications Categorization

	References
Manufacturing	Assaqty et al. (2020) Cambou et al. (2020) Westerkamp et al. (2020) Chang (2020) Tozanlı et al. (2020) Alkhader et al. (2020) Mandolla et al. (2019) Ko et al. (2018) Kennedy et al. (2017)
Supply Chain	Bhaskar et al. (2020) (Epiphaniou et al., 2020) Katsikouli et al. (2021) (Tang and Zhuang, 2020) Kumar et al. (2020) (Zhang et al., 2020b) Li et al. (2020a) Bullón Pérez et al. (2020) Cao et al. (2020) Gajek et al. (2020) Venkatesh et al. (2020) Zelbst et al. (2019) Li et al. (2020b) Iqbal and Butt (2020) Wang et al. (2020) Debe et al. (2020) Gao et al. (2020) Hasan et al. (2020) Manupati et al. (2020) Violino et al. (2019) Kurpjuweit et al. (2021) Rahmanzadeh et al. (2020) Prause (2019) Fan et al. (2020) Jabbar and Dani (2020) Montecchi et al. (2019) Scuderi et al. (2019) Lin (2019) Banerjee (2019) Salah et al. (2019) Lin et al. (2019) Fu and Zhu (2019) Mao et al. (2018) Banerjee (2018) Probst (2020) Rejeb et al. (2019) Sharma et al. (2019)
Applications in general	Bodkhe et al. (2020) Zhu et al. (2020) Tappuni (2020) Pazaitis (2020) Liu et al. (2020)
Field studies	Kurpjuweit et al. (2021) Mandolla et al. (2019) Bullón Pérez et al. (2020) Cao et al. (2020) Violino et al. (2019) Scuderi et al. (2019) Lin (2019) Fu and Zhu (2019) Lohmer and Lasch (2020) Chen et al. (2020)Bumblauskas et al. (2020) Pan et al. (2020) Lähdeaho and Hilmola (2020) Sheel and Nath (2019) Hartley and Sawaya (2019) Chang (2020)
Literature Review	Rejeb et al. (2019) Zuo (2020) Balzarova (2020) Kshetri and DeFranco (2020) Sobb et al. (2020) Dutta et al. (2020) Leng et al. (2020) Erokhin et al. (2020) Rodrigo et al. (2020) Rymarczyk (2020)