A holistic approach to challenges in Industry 4.0

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Abstract. *During the last decades, a series of cutting-edge Information and Communication Technologies (ICTs) gained momentum in industry and academia. Including several technologies such as the Internet of Things, Clouds, and Smart Sensors, to name a few. As a digital paradigm that fosters decentralized planning and control along with mass personalization in manufacturing, Industry 4.0 is currently paving the road to a fourth industrial revolution. In this paper, we depict important challenges in this context of ICTs and mass personalization of Industry 4.0, ambitioning the achievement of conflicting production goals of price and customization. In our holistic vision, we discuss these challenges under both the prisms of computer science and production engineering.*

Resumo. *Durante as últimas décadas, uma série de Tecnologias de Informação e Comunicação (TICs) de ponta ganhou força na indústria e na academia. Incluindo várias tecnologias, como por exemplo a Internet das coisas, computação em nuvem e sensores inteligentes. Como um paradigma digital que promove o planejamento e o controle descentralizados, juntamente com a personalização em massa na manufatura, a Indústria 4.0 está atualmente abrindo caminho para uma quarta revolução industrial. Neste artigo, apresentamos desafios importantes neste contexto de TICs e personalização de massa da Indústria 4.0, ambicionando a realização de objetivos de produção conflitantes de preço e customização. Em nossa visão holística, discutimos esses desafios sob os prismas da ciência da computação e da engenharia de produção.*

1. Introduction

During the last decades, a series of cutting-edge Information and Communication Technologies (ICTs) gained momentum in industry and academia. Among such technologies, we cite the Internet of Things (IoT), Cloud Computing and Blockchain [Parwekar 2011, Viryasitavat et al. 2018], to name a few. The convergence of these recent ICTs into business and applications that are typical of industrial environments is the core of the Industry 4.0 paradigm. This novel industrial paradigm is so expressive that it is currently paving the road to a whole fourth industrial revolution [Lu 2017].

As digital paradigms, Industry 4.0 brings expected benefits to the manufacturing. It (i) enables competitive advantages to the firms, (ii) shortens distances among them, (iii) makes them more decentralized and autonomous, (iv) speeds up the delivery of their products/services and (v) enables the flexible production of a broad variety of new products/services to them [Wang et al. 2017, Lu 2017]. With the features of Industry 4.0, companies start pursuing new decentralized structures that privilege flexibility and autonomy of the productive nodes in the supply chain. Along with industry 4.0, the new paradigm of mass personalization arises, in which the markets are embodied with the active participation of consumers since the earliest stages of product design, until delivery[Wang et al. 2017]. This set of features creates a scenario that fosters decentralized planning and control strategies, along with mass personalization in manufacturing.

Despite its benefits, it is important to mention that Academia and Industry currently have no exact definition of Industry 4.0, and several expectations exist in future. Moreover, the way in which Industry 4.0 supports the mass personalization paradigm is also not clear, while only a few proposals exist, such as the one of Wang et al. [Wang et al. 2017]. In this context, several significant challenges arise in Industry 4.0. Including how to manage the common manufacturing resources, integrated by the ICTs along multiple productive and autonomous cells, to achieve the conflicting production goals (regarding price and customization) that are typical of mass personalization.

In this paper, we depict important challenges in this context of ICTs and mass personalization of Industry 4.0. Among our contributions, we present a holistic vision to these challenges, discussing them under both the prisms of computer science and production engineering. Thus, we also raise new opportunities for research in the field of Industry 4.0. In Section 2, we discuss the emergence of Industry 4.0 and mass personalization paradigms. In Section 3, we describe key ICTs from the Industry 4.0 paradigm. In Section 4, we discuss challenges and research directions in Industry 4.0. Section 5 concludes this work.

2. The emergence of mass personalization

The manufacturing activity has been playing an important role in our society in last centuries, during which it also has undergone several transformations. It is important to discuss the current state of evolution in manufacturing to understand where the fourth industrial revolution takes place.

According to Wang et al. [Wang et al. 2017], the production paradigm has undergone three revolutions and is currently experiencing a fourth revolution. A first industrial revolution occurred in England, during the 18th century, influenced, among others, by the invention of steam engines. This allowed the Craft Production (CP), in which products were manufactured based on the users' requirements, showing high cost and with a limited volume. A second industrial revolution happened at the beginning of the 20th century, driven by advances in precision engineering, division of labor, standardization, and assembly line work. This allowed Mass Production (MPR), providing low-cost and low-variety products made using large-scale production systems. The third industrial revolution emerged in the late 20th century, based on advances in information sciences, automation technology, and the computer. In this period, flexible production was developed, providing products with low cost and large varieties, raising the concept of Mass

Customization (MC).

In MC, the objective is to provide products that meet the requirements of each consumer (customization) at a low cost that resembles the cost achieved in MP. There is a clear and traditional conflict between these two features to the consumer, of customization and low cost [Wang et al. 2017, Tseng and T.Piller 2003]. This conflict occurs since low costs are more easily obtained by production structures that foster standardization of products and processes, than by production structures that foster customization of products and processes. Mitchell and Tseng [Tseng and T.Piller 2003] state that MC is a competitive advantage based on the combination of the MP's efficiency and the customization's differentiation possibilities. In every aspect, MC is the current status of the third industrial revolution. According to Wang et al. [Wang et al. 2017], a current trend exists in MC, which refers to shifting focus from the value of the company to the customer demand. The last one is a key driving force leading to the fourth industrial revolution, which is, therefore, characterized by Mass Personalization (MPE).

In MPE, the key feature is active customer participation in the production process. In typical markets of the fourth industrial revolution, consumer requirements related with user experience are becoming increasingly relevant. To meet them, the production process is integrated with customers. This integration allows customers to express their creativity, while obtaining value. Thus making their desires a reality by their cooperation with manufacturers. As a matter of comparison, an important aspect of MC is obtained from modularity and reuse. Thus, several product variants can be configured by the manufacturer in the form of product families, while the design decisions are held by the manufacturer. In contrast, in MPE, the integral product, including final product and its design, has to be changeable, adaptable and configurable at the level of module and parameter, to meet the user's unique need for experience. Companies move towards MPE with the help of the cutting edge ICTs from Industry 4.0, which provide companies with competitive advantages such as cost, quality, flexibility, time, and variety. In next Section, we describe some of these ICTs.

3. Emerging technologies in Industry 4.0

In this Section, we introduce ICTs that we consider most relevant, for grounding the Industry 4.0 paradigm in our vision. These are the Clouds of Sensors (Section 3.1) and the Blockchain (Section 3.2) technologies.

3.1. Clouds of Sensors

The current definition of the Internet of Things (IoT) paradigm envisions a global network infrastructure, linking physical and virtual objects by employing resources of data capture and communication [Parwekar 2011]. Combining the Cloud Computing and IoT paradigms brings mutual advantages for both, resulting in the emergence of the Cloud of Things (CoT) paradigm [Parwekar 2011]. The IoT benefits from the virtually unlimited capabilities and resources of Cloud. On the other hand, the Cloud benefits from IoT by extending its scope to deal with real world things in a more distributed and dynamic manner. Among devices connected to the CoT, there are the smart sensors. These are devices endowed with processing, storage, sensing, actuation, and wireless communication capabilities. Such capabilities enable these sensors to be grouped together for cooperatively monitoring variables, enabling the concept of Wireless Sensor and Actuator

Networks (WSAN). Throwing focus on WSANs, the Cloud of Sensors (CoS) paradigm [Madria et al. 2014] emerges as a specific type of cloud within the CoT.

A CoS is composed of virtual sensors built on top of physical wireless sensors, which users automatically and dynamically can provision based on applications demands [Madria et al. 2014]. Moreover, data captured by WSNs can be shared among multiple users, which reduces the overall cost of data collection for both the system and user. In particular, because the CoS infrastructure is open, flexible, and reconfigurable, it is suitable and beneficial for monitoring and controlling applications which require large-scale WSAN deployments, such as the industrial applications that fall within the mass personalization paradigm.

3.2. Blockchain

A Blockchain is a distributed data structure that is replicated and shared among the members of a network [Viryasitavat et al. 2018]. Each block consists of a set of transactions and a hash. The chain is started with the genesis block (common to all clients). The genesis block hash is used as input to the hashing function along side with the current block, resulting into a new hash that signs the current block. From now on, the hash function output is the hash of the previous block and the current block. Thus, each block in the chain carries a list of transactions and a hash to the previous block. A transaction is an operation over a tokenized asset of a node of the Blockchain in favor of other node of the Blockchain.

Then, Blockchain can be understood as a log whose records are mapped into signed blocks. A signature of a block is its cryptographic hash. Since every hash is function of the hash of the previous block, a unique link between blocks is established over a chain of blocks and brings authentication, integrity, and non-repudiation into the network. In next Section, we describe the research directions in Industry 4.0, grounded on the technologies described in this Section.

4. Research directions in Industry 4.0

The emergence of IoT is envisioned to transform many aspects of society's everyday activities. This inexorable transformation has the potential to reach (i) the way customers buy their products, (ii) the traditional product manufacturing requirements and processes and (iii) the way that the supply-demand balance is reached. Among the technologies that enable such transformation, there is the smart contract technology [Viryasitavat et al. 2018], based on Blockchain technology.

The concept behind smart contracts consists of a computerized transaction protocol that executes the terms of a contract. Roughly, they are contractual clauses (business rules) to be enforced by the system. For financial purposes, within the Blockchain context, smart contracts are scripts stored on the Blockchain. Their objective is to minimize both the need for trusted intermediaries between transacting parties and the occurrence of malicious or accidental exceptions. A smart contract is triggered by addressing a transaction to it. When triggered, the smart contract is executed, automatically on every node of the network. Since the smart contract resides on the chain, it receives a unique address.

In the Industry 4.0 context, the role of a smart contract is to carry the information of the critical path to the execution of a set of operations needed to meet the requirements of a manufacturing and/or logistic process. For example, the manufacturing activity can be modeled as decomposed into a work flow of operations that have to be performed to produce a given product. The order in which the operations are applied matters and should the embedded into the manufacturing process and the production chain design. With the aid of RFID and WSAN infrastructures, each operation of the production chain can be identified and its execution monitored. Such systems can become integrated through the Internet, composing networks of intelligent, distributed and autonomous cell factories.

These smart factories can be distributed along the most diverse geographical regions, urban or rural, and be fully integrated with humans' habitation spaces. For instance, each person is able to own a small flexible manufacturing plant in its home nowadays, due to the advances in 3D printing. Leaving the discussion from the real environment, and heading towards the virtual environment, these networks of smart factories can become organized into a cloud fashion. The resources of each smart factory can be shared collaboratively among multiple users, bringing value to customers in the form of user experience, typical from mass personalization. With this respect, users are the owners of product design and fabrication, breaking typical centralized production/economic structures and fostering collaboration to meet user's demands. This gives birth to a new paradigm, which we call the Cloud of Factories (CoF). The CoF allows the fabrication and delivery of products closer to the places where they are demanded. The lead times are reduced for this reason, and also because of eliminating the intermediary manufacturer. Flexibility is a key benefit achieved, since users' collaboration enables a series of new products to be delivered among themselves.

Other minor challenges faced in the context of CoF are as follows. First, it is necessary to investigate how to perform big data and social network analysis [Tan et al. 2013] to foster collaboration among customers and producers in cities, realizing the mass personalization paradigm.

Second, to perform the virtualization of WSAN in CoS, it is necessary to ensure (i) the flexibility of the sensing infrastructure, (ii) the stability of applications and, in the event of instability, convergence to a stable state, and (iii) the isolation of the virtual sensor networks created to suit each application. To overcome them, it is possible to relate the MapReduce programming model [Dean and Ghemawat 2008] and a WSAN virtualization model, in the form of a MapReduce runtime environment for CoS applications.

Third, since the factory assets will become distributed among consumers, the depreciation of such assets is a challenging issue to be faced by consumers. Investigating new methods for performing structural health monitoring (SHM) and condition based maintenance (CBM) [dos Santos et al. 2014] of such assets through decentralized strategies is therefore necessary.

Finally, the digitalization of agriculture recently introduced new tools and machines in agriculture. Concurrently, new sustainable approaches are desired to face the problem of limited agricultural areas we have available. To surpass this limitation, research addressing the subject of agriculture in urban areas has been conduced, converging to the smart vertical farming paradigm [Benke and Tomkins 2017]. As a major challenge in this context, solutions can be researched to fully integrate smart vertical farms to distributed factories, in the CoF paradigm.

5. Conclusion

In this work, we depicted relevant challenges in Industry 4.0, involving relevant ICTs and mass personalization. Thus, we presented our holistic vision, raising new opportunities of research in this field. We also discussed the paradigm of Clouds of Factories. With our vision, we aim at contributing to fostering a society based on the creative economy, in which humans will be instigated to develop their full potential, supported by the delivery of products and services in real time scale. As future work, we plan to explore each of the challenges raised in this work in detail, demonstrating the potential of the CoF technically.

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