Technological Theory of Cloud Manufacturing

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Abstract Over the past decade, a flourishing number of concepts and architectural shifts appeared such as the Internet of Things, Industry 4.0, Big Data, 3D printing, *etc*. Such concepts are reshaping traditional manufacturing models, which become increasingly network-, service- and intelligent manufacturing-oriented. It sometimes becomes difficult to have a clear vision of how all those concepts are interwoven and what benefits they bring to the global picture (either from a service or business perspective). This paper traces the evolution of the manufacturing paradigms, highlighting the recent shift towards Cloud Manufacturing (CMfg), along with a taxonomy of the technological concepts and technologies underlying CMfg.

1 Introduction

Manufacturing paradigms evolved over time, driven by societal trends, new ICT (information and communication technology) technologies, and new theories. The manufacturing processes of the future need to be highly flexible and dynamic in

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order to map the customer demands, e.g. in large series production or mass customization. Manufacturing companies are not only part of sequential, long-term supply chains, but also of extensive networks that require agile collaboration between partners. Companies involved in such networks must be able to design, configure, enact, and monitor a large number of processes and products, each representing a different order and supply chain instance. One way of achieving this goal is to port essential concepts from the field of Cloud Computing to Manufacturing, such as the commonly applied SPI model: SaaS (Software-as-a-Service), PaaS (Platform-as-a-Service), IaaS (Infrastructure-as-a-Service) [18]. In the literature, this concept is referred to as "Cloud manufacturing" (CMfg), which has the potential to move from production-oriented manufacturing processes to customer- and service-oriented manufacturing process networks [15], e.g. by modelling single manufacturing assets as services in a similar vein as SaaS or PaaS solutions.

While organizations will be looking to make use of CMfg for creating radical change in manufacturing practices, this will not be an easy transition for many. There will be architectural issues as well as structural considerations to overcome. The main reason for this is that CMfg derives not only from cloud computing, but also from related concepts and technologies such as the Internet of Things – IoT (core enabling technology for goods tracking and product-centric control) [8, 3], 3D modeling and printing (core enabling technology for digital manufacturing) [2, 12], and so on. Furthermore, some of those concepts/technologies have not yet reached full maturity such as the IoT, whose number of connected devices should pass from 9.1 billion (2013) to 28.1 billion (2020) according to IDC forecasts). Similarly, while 3D modeling is now conventional even for small companies, 3D printing is still in the peak of inflated expectation phase in the Gartner Hype Cycle, which may be (potentially) followed by a drop into the trough of disillusionment [13]. Within this context, the success of CMfg is partly dependent upon the evolution of all those concepts, although it is often difficult to understand how they are interwoven and how important one is to the other. The present paper helps to better understand such interwoven relationships, the current trends and challenges (e.g., shift from closed-industry solutions to open infrastructures and marketplaces).

To this end, section 2 shows the evolution of the manufacturing paradigms through the ages. Section 3 introduces a CMfg taxonomy, whose key challenges and opportunities of the underlying concepts are discussed, the conclusions follow.

2 Manufacturing Paradigms Through The Ages

Over the last two centuries, manufacturing industry has evolved through several paradigms from Craft Production to CMfg [4, 9]. Craft Production, as the first paradigm, responded to a specific customer order based on a model allowing high product variety and flexibility, where highly skilled craftsmen treated each product as unique. However, such a model was time- and money-consuming – *as depicted*

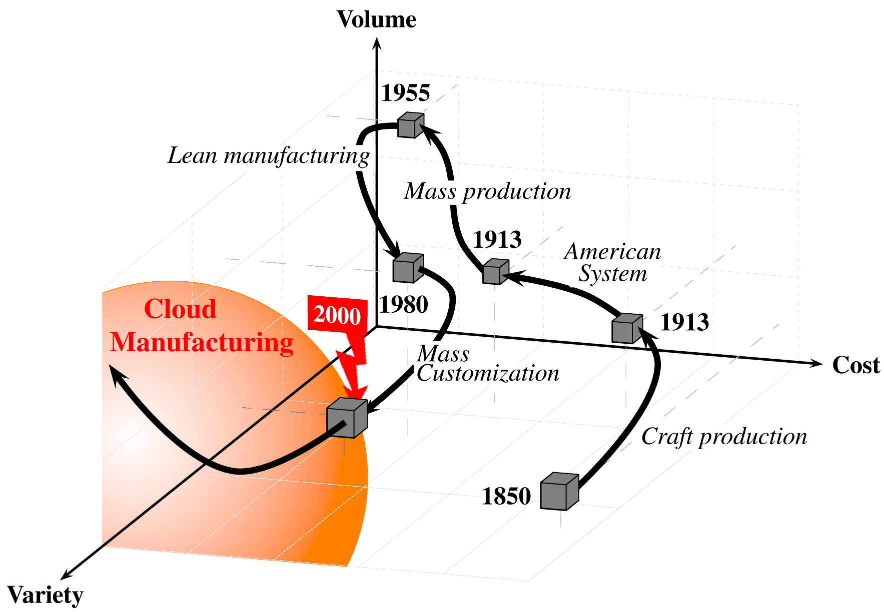

Fig. 1 Volume-Variety-Cost relationship in manufacturing paradigms

in Fig. 1. The history of production systems truly began with the introduction of standardized parts for arms, also known as the "American System" (see Fig. 1).

Following the American System model, Mass Production enabled the making of products at lower cost through large-scale manufacturing. On the bad side, the possible variety of products was very limited since the model is based on resources performing the same task again and again, leading to significant improvement of speed and reduction of assembly costs (*cf.* Fig. 1). Symbols for mass production were Henry Ford's moving assembly line and his statement: *"Any customer can have a car painted any color that he wants so long as it is black"*.

Lean Manufacturing emerged after World War II as a necessity due to the limited resources in Japan. The Lean Manufacturing paradigm is a multi-dimensional approach that encompasses a wide variety of management practices, including just-in-time, quality systems, work teams, cellular manufacturing, *etc.*, in an integrated system [22] that eliminates "waste" on all levels. It is worth noting that the lean management philosophy is still an important part of all modern production systems.

The fourth paradigm, Mass Customization, came up in the late 1980's when the customer demand for product variety increased. The underlying model combines business practices from Mass Production and Craft Production, moving towards a customer-centric model. This model requires the mastery of a number of technologies and theories to make manufacturing systems intelligent, faster, more flexible, and interoperable. Within this context, a significant body of research emerged, particularly with the IMS (Intelligent Manufacturing System) community with worldwide membership, which is an industry-led, global, collaborative research and development program established to develop the next generation of manufacturing and processing technologies. The IMS philosophy adopts heterarchical and collaborative control as its information system architecture [23, 19, 17]. The behavior of the entire manufacturing system therefore becomes collaborative, determined by many interacting subsystems that may have their own independent interests, values, and modes of operation.

It is clear from Fig. 1 that the manufacturing paradigms succeeded one another, always seeking for smaller volumes and costs, while rising the product variety. The fifth and recent paradigm, CMfg, moves this vision a step further since it provides service-oriented networked product development models in which service consumers are enabled to configure, select, and use customized product realization resources and services, ranging from computer-aided engineering software to reconfigurable manufacturing systems [16, 26]. Several applications relying on Cloud infrastructure have been reported in recent years, e.g. used for hosting and exposing services related to manufacturing such as machine availability monitoring, collaborative and adaptive process planning, online tool-path programming based on real-time machine monitoring, collaborative design, *etc.* [25, 21]. Similarly in the European sphere, this technology has recently attracted a lot of attention, e.g. with the Future Internet Public Private Partnership (FI-PPP)[1], OpenStack, OpenIoT[2], or Open Platform 3.0 communities[3].

The next section helps to understand what concepts and technologies are underlying CMfg, how they are interwoven together, how important one is to the other, and what challenges remain ahead.

3 Cloud Manufacturing Taxonomy

The Industrial Internet, Industry 4.0, CMfg, or still Software Defined Manufacturing (SDM) are terms referring to the new phenomenon (or next wave) of innovation impacting the way the world connects and optimizes machines, as well as information systems in the manufacturing industry. In CMfg applications, various manufacturing resources and abilities can be intelligently sensed and connected into a wider Internet, and automatically managed and controlled using both (either) IoT and (or) Cloud solutions, as emphasized in the taxonomy given in Fig. 2. In this taxonomy, one can see that the so-called IoT is a core enabler, if not the cornerstone, for product-centric control and increasing servitization (i.e., making explicit the role of the product as the coordinating entity in the delivery of customized products and services) [10]. Product-centric control methods are, in turn, required and of the utmost importance for developing fast and cost effective Direct Digital Manufacturing

[1] http://www.fi-ppp.eu
[2] https://github.com/OpenIotOrg/openiot/wiki/OpenIoT-Architecture
[3] http://www.opengroup.org/subjectareas/platform3.0

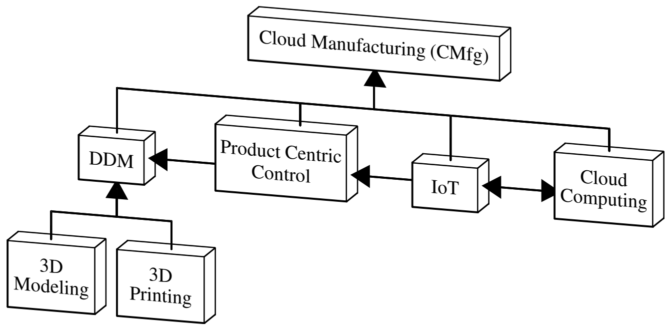

Fig. 2 CMfg Taxonomy: underlying concepts and technologies

(DDM) solutions [12], also known as 'Rapid Manufacturing'. One example of how CMfg platforms combine all those concepts might be the following:

> *"a tractor (or backend system) detects – based on sensor data fusion – that the pump is defective. The after-sales service system is immediately notified and turns to the services of the cloud manufacturing community to i) access product-related data and models (e.g., CAD models) and then ii) identify an optimal manufacturer for the broken pump parts. The digital model is sent to the community member who can produce the custom part via 3D printing. The closest (or cheapest) 3D printer service provider(s) can be discovered (e.g., via IoT discovery mechanisms), so that the pump part can be produced to order and shipped to the farmer."*

Sections 3.1 to 3.4 discusses in greater detail all the taxonomy concepts and interdependencies, along with challenges that still need to be addressed.

3.1 Cloud Computing

Cloud computing has revolutionized the way computing infrastructure is abstracted and used [18]. The benefits of Cloud for manufacturing enterprises are numerous; Cloud as a procurement model delivers undisputed cost efficiencies and flexibility, while increasing reliability, elasticity, usability, scalability and disaster recovery. A key difference between Cloud computing and CMfg is that resources involved in cloud computing are primarily computational (e.g., server, storage, network, software), while in CMfg, all manufacturing resources and abilities involved in the whole life cycle of manufacturing are aimed to be provided for the user in different service models [15]. The manufacturing resources and abilities are virtualized and encapsulated into different manufacturing cloud services, where different product stakeholders can search and invoke the qualified services according to their needs, and assemble them to be a virtual manufacturing environment or solution to complete their manufacturing task [26].

As an end consumer looking at the cloud space, there are two major types of clouds to choose from: open source clouds (e.g., Citrix, OpenIoT) and closed clouds

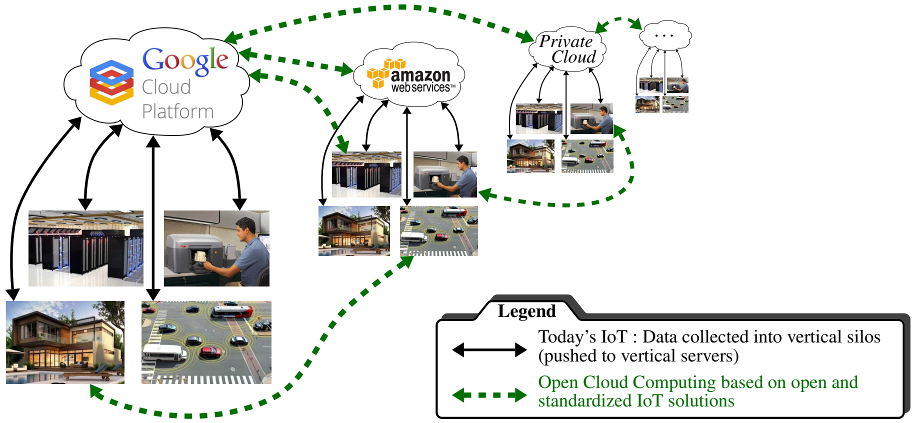

Fig. 3 Challenge of creating CMfg ecosystem based on open IoT standards

(e.g., Amazon, Azure, Google). One of the key challenges, especially from the EU perspective, is to foster cloud manufacturing based on existing open standards and components to facilitate an as-vendor-independent-as-possible Cloud engineering workflows platform, which should lead to radical transformations in business dynamics in the industry (e.g., for new open standard-based value creation) [24, 6]. This implies creating cloud manufacturing ecosystem(s) built on open IoT messaging standards having the capabilities to achieve "Systems-of-Systems" integration, as will be discussed in the next section.

3.2 Internet of Things (IoT)

The growth of the IoT creates a widespread connection of "Things", which can lead to large amounts of data to be stored, processed and accessed. Cloud computing is one alternative for handling those large amounts of data. To a certain extent, the cloud effectively serves as the brain to improve decision-making and optimization for IoT-connected objects and interactions [27], although some of those decisions can be made locally (e.g., by the product itself) [19, 17]. However, as stated previously, new challenges arise when IoT meets Cloud; e.g. creating novel network architectures that seamlessly integrate smart connected objects, as well as distinct cloud service providers (as illustrated with the dashed arrows in Fig. 3). IoT standards e.g. for RESTful APIs and associated data will be key to be able to import/export product-related data and models inside CMfg ecosystems [20].

Several research initiatives have addressed this vision such as – *in the EU sphere* – the IERC or FI-PPP clusters (see e.g. FI-WARE, OpenIoT), or still the Open Platform 3.0 (initiative of The Open Group). In this respect, our research claims that the recent IoT standards published by The Open Group, notably O-MI and O-DF [8], have the potential to fulfill the "Systems-of-Systems" vision discussed above. O-MI provides a generic Open API for any RESTful IoT information system, and O-DF is a generic content description model for Objects in the IoT, which can be extended with more specific vocabularies (e.g., using or extend domain-specific ontology vocabularies). Both standards are about to be used as foundation of the upcoming H2020 project bIoTope (Building an IoT OPen innovation Ecosystem for connected smart objects), where proofs of concept and value of open CMfg ecosystems will likely be developed. Furthermore, O-MI and O-DF specifications were identified from several real-life industrial applications of the PROMISE EU project (including manufacturing scenarios) [7], thus making it suitable for effective Product Centric Control, as will be discussed in the next section.

3.3 Product Centric Control

In a true IoT, each intelligent product and equipment is uniquely identifiable [1], making it possible to link control instructions with a given product-instance. The basic principle is that the product itself, while it is in the process of being produced and delivered, directly requests processing, assembly and materials handling from available providers, therefore simplifying materials handling and control, customization, and information sharing in the supply chain. This concept is referred to as "Product Centric Control" [11], which is required and of the utmost importance from a CMfg perspective since it allows for developing fast and cost effective DDM solutions, as will be discussed in the next section. Indeed, operations and decision making processes that are triggered and controlled by the product itself result in higher quality and efficiency than standard operations and external control. The generative mechanism is somehow the ability of the product to *i)* monitor its own status; *ii)* notify the user when something goes wrong (e.g., the defective pump); *iii)* help the user to find and access the necessary product-related models and information from the manufacturer community involved in the CMfg ecosystem; and *iv)* ease the synchronization of product-related data and models that might be generated in distinct organizations, throughout the product lifecycle [19, 14].

3.4 Direct Digital Manufacturing – DDM

Recently, the range of DDM[4] technologies has increased significantly with the advancement of 3D printing [12], opening up a novel range of applications considered impossible, infeasible or uneconomic in the past. DDM technologies are technologies that include both novel 3D printing and 3D modeling (as emphasized in Fig. 2), i.e. the more conventional numerical controlled machines. The need for tooling and setup is reduced by producing parts directly based on a digital model. The impli-

[4] DDM is the usage of additive manufacturing for production of end-use components.

cation of the development of DDM technologies is that, in an increasing number of situations, it is possible to produce parts directly to demand, without tooling, setup and consideration of economies of scale [5]. Time-to-market, freedom of design, freedom to redesign and flexible manufacturing plans are only the beginning. These advantages represent just the tip of the iceberg since DDM is a relatively new manufacturing practice.

Given this, CMfg is clearly an applicable business model for 3D-printing. Because additive manufacturing is a digital technique, it is possible to manufacture products close to the location where they will be used, thus reducing transportation (Co2 emissions), large storage areas, while enabling a wide range of customers, suppliers and manufacturers to take part to the development of new products and services based on an open and standardized CMfg platform.

4 Conclusion

In industry, cloud manufacturing (CMfg) platforms are rarely applied today because of considerable concerns about security and ROI (due mainly to considerable efforts to implement interoperability). Furthermore, the maturity of the platforms is often limited to a prototype status nowadays. However, there are some industry settings, from which interest in such a concept is stated such as associations of SMEs who intend to jointly provide customisable products, or industry clusters who would like to make their members' abilities easily available (searchable and usable) for other members.

Within this context, the emergence of the Internet of Things, Cloud computing, 3D printing, product-centric-control techniques, *etc.*, mark a new turning point for CMfg – manufacturing resources and organization assets become easier to be remotely tracked, monitored, accessed, booked and used (e.g., for production), when and as needed. However, all those concepts make it difficult to understand how they are interwoven and what benefits they bring to the global picture (either from a service or business perspective). This paper contributes to the discussion about this global picture with the introduction of a CMfg taxonomy, while discussing current trends and challenges that still face CMfg (e.g., shift from closed-industry solutions to open infrastructures and marketplaces). In this regard, this paper claims that the vision of "Systems-of-Systems" built on open standards (e.g., open IoT standards as O-MI/O-DF) will be key in the future to develop more advanced open- and customer-oriented CMfg models, which will result in innovative business transformation services.

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