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Platform-based manufacturing

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ABSTRACT

Platform-based manufacturing is substantially changing the way production is conceived and performed. Companies do not know who is making their parts, part manufacturers do not necessarily own the machines, and knowledge and decisions cross the borders of firms. This revolutionary approach is already becoming a reality thanks to a wealth of innovations related to manufacturing science as well as information and communication technologies, and novel business models that meet together at the right moment of their evolution. Considering the existing literature and digging into the phenomenon by interviewing decision-makers, the paper reconstructs the roots of these developments, analyzes the challenges posed to the manufacturing sector, focuses on recent challenges and opportunities, and finally delineates visions for the future.

1. Introduction

The discrete manufacturing industry has entered a new era of connectivity and the shared use of information, material, intellectual and financial assets. As a recent development, more and more sophisticated information and communication technologies (ICT)—indeed, almost the whole armory of Cyber-Physical Production Systems (CPPS) [174]—have been invested in functionalities which are provided by so-called *platforms*. Platforms are designed to support business applications that are going to solve business problems. They are helpful because they abstract common functions away from the specific application logic. New manufacturing-related platforms are appearing on the market practically every week and the already functioning platforms are growing very quickly, in some cases at a two-digit speed. These platforms enter the market as new players, with novel *service* offerings and business models [130]. They are key elements of *equipment-as-a-service* (EaaS) and *production-as-a-service* (PaaS) [128] businesses, where instead of owning manufacturing resources, producers pay a fee for using machines, or even complete factories, respectively. Some platforms define even a global technological ecosystem for *smart manufacturing* [129], by offering a stack of Industrial Internet of Things (IIoT) services [26]. Some of these platforms acquire manufacturing and service companies and merge again with other platforms. Some platforms are already signing agreements to supply big companies and some platforms already rely on thousands of suppliers. Therefore, a platform economy in manufacturing is not just an idea, it is a rising wave and will have a deep impact on the way manufacturing is conceived and performed in the future.

This keynote departs from in-depth studies of some existing platforms obtained by interviewing various platform providers and users, analyzes and classifies their connected services, and puts the platform wave into the context of existing knowledge, methodologies, and tools that made possible the evolution of *platform-based manufacturing* (PBM). The core ideas are quite simple: design a product, load the product design on a platform, and have it manufactured at a manufacturer unknown to the customer and delivered by a logistics provider in a short time, with the required quality and quantity. It may look similar to e-marketplaces like Amazon and Alibaba, although one important difference is that the product is not selected from a catalog, but it is manufactured on demand. Alternatively, instead of possessing manufacturing equipment, related software services, or even a complete facility, companies can hire and use them as and when needed and pay for this service.

As simple as it may seem, this idea has the potential of shaking the whole manufacturing sector from the ground. In addition, it is already underway. The reason for this is that manufacturing-related platforms have in comparison with classical companies a different business model and organize the traditional functions of the company in a different way. Variants of PBM are now finding their way into the economy, by cooperating and competing with traditional actors and winning areas of influence. Therefore, it is interesting to understand how PBM has evolved and anticipate future trends which call for interdisciplinary research. The paper summarizes interviews with experts who operate various platforms and carries out a study reviewing and analyzing research papers which provide the theoretical foundations. Indeed, there is a need to understand the roots of this phenomenon based on what is already known from existing literature, but at the same time, there is also a need to analyze what is happening and understand the potential future developments. One of the goals of the paper is to identify areas where existing knowledge is not sufficient to support platforms and therefore new knowledge needs to be generated throughout research and development.

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The paper investigates PBM and its relationships to other types of platforms such as innovation, product, energy, or mobility platforms. These platforms cover different areas but together create a new concept of the *platform economy*. Particular emphasis will be dedicated to platforms that have a direct connection to the design and operation of manufacturing systems. The focus will be set on the rising platforms which provide new opportunities in two respects: (1) the ownership of all kinds of manufacturing assets and (2) the market access (Fig. 1). All the possibilities are meaningful and already have real cases. The extreme case is when the product is sourced from a platform and the software or equipment to manufacture it is provided by an operational or equipment platform (IV in Fig. 1). This concept is further clarified in the next section.

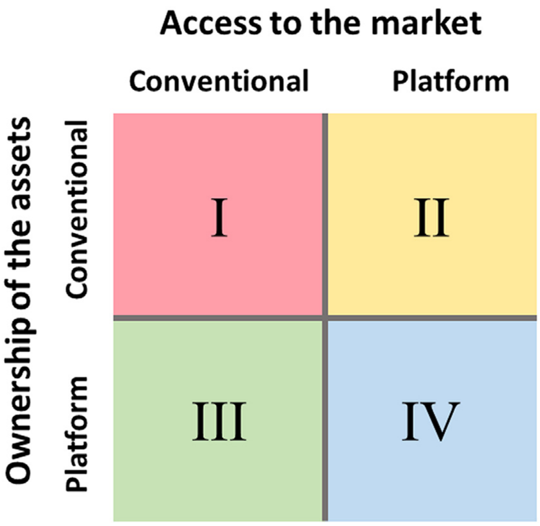


Fig. 1. Conventional vs. platform-based manufacturing.

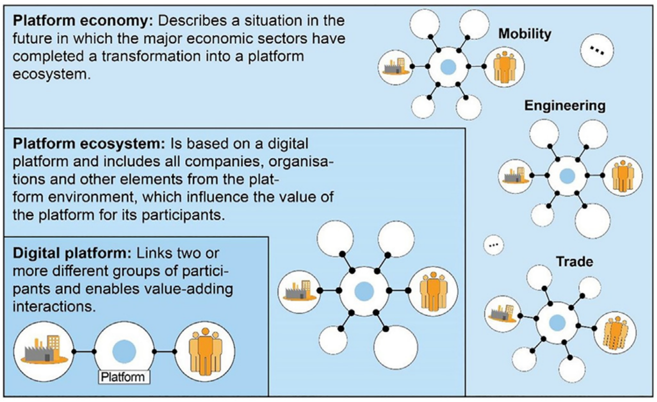
How can in this new scenario the *manufacturing industry*—traditionally focused on physical assets such as machines to be built and efficiently operated, and parts to be produced—keep its position as an important contributor to welfare and economic growth? As it always happens in a revolution, there will be winners and losers. Therefore, it is very important for companies and countries alike to anticipate the change and take the necessary steps to find a new successful positioning. In the platform economy, traditional relations in the supply chain are completely modified and new models of business and actors appear. The role of each company changes, as well as its organization and management structure and the performed activities. The whole way of manufacturing is shaken from the ground and a new manufacturing era may start. The question is how manufacturing companies, and the providers of manufacturing equipment, technologies, and services (like machine builders) can participate in the evolution of the platform economy, generating revenues from not only selling “heavy metal”, but also value-adding services. For instance, a joint study by the German Association of Mechanical and Plant Engineering (VDMA) and McKinsey came to the result that complex digital services including sensor and control technologies, device and inter-firm connectivity, big data infrastructures, application-enabling backend as well as frontend software are major growth drivers for machine builders and component suppliers. Specifically, while in 2019, the share of sales of digital platforms and value-adding services was only app. 0.7% in the entire machine market in Western Europe (in total ca. €850 billion), the market for such services is expected to increase to ca. €64 billion by 2024 [261]. Whereas this forecast refers mainly to a variant of PBM what we termed operational platform (see Section 2), it is reasonable to assume that this growth trend applies to PBM in general as well. Indeed, one of the goals of this paper is to facilitate this evolution by providing a better understanding of PBM. A recent market analysis by the Boston Consulting Group surveying 1500+ global companies both in industrialized and emerging economies reveals that the annual investments in production assets used in any PaaS model could reach ca. $70-$100 billion globally, while the annual manufacturing value-added by PaaS setups could reach ca. $720-$900 billion [128]. Already in the short term, up to 15% of production operations can be set up in a PaaS model depending on the specific industry and country.

The availability of digital technologies and the proliferation of new service models can in principle trigger various evolutions in the market. Some very interesting models have been proposed in the literature which could be developed and could become part of the future manufacturing scenario. Some of these models have certainly inspired the creation of manufacturing platforms. Most of the models show the opportunities of joining efforts among companies in a win-win situation. The main difference between these models for the manufacturing platforms analyzed in this paper is that manufacturing platforms are new actors strongly based on *competition* and the acquisition of some functions previously performed by classical companies. They do not share manufacturing-related experience and knowledge, just on the contrary, they tend to keep it separate and avoid communication between customers and suppliers and they are struggling to guarantee the privacy of the information of their customers. They are real, operating, and growing very fast. A definite goal of this paper is to discern what ideas can contribute to turning this scenario into a more cooperative one, to the benefit of a more resource and energy-efficient, sustainable manufacturing.

1.1. *Definitions and scope of the paper*

In the context of increasing digitalization, there are some signs of potential disruption, i.e., a radical transformation of the existing business landscape induced by the emergence of new business models and a completely new range of products and services. In manufacturing and the related automation technology, the changes brought about by CPPS and Industry 4.0 resemble an evolution despite their strong disruptive effects [172,174]. However, driven by the developments in ICT and business-to-customer (B2C) markets as well, platforms in any appearance may indeed change the manufacturing industry, the machine builder industry, and the entire business-to-business (B2B) scenario.

In the manufacturing practice, already several notions of platforms prevail. Platforms include the technological basis to develop and run software applications [196] that support either the machining processes themselves or the exchange of data to improve the entire process chains. Alternatively, platforms connect buyers and sellers, customers and suppliers by providing matchmaking functions between two or more market participants. There are digital marketplaces in manufacturing, too, e.g., for digital sourcing of spare parts [86]. Platforms also enable the participants' interaction and their exchange of products, services, data and/or currencies. They facilitate classical business interactions between the business partners or enable completely new types of interactions by involving customers also into the innovation process [46,193]. PBM is only one part of the global platform economy, connecting the different economic sectors that have undergone a transformation into the related platform-based ecosystems (see Fig. 2).



Platform economy: Describes a situation in the future in which the major economic sectors have completed a transformation into a platform ecosystem.

Platform ecosystem: Is based on a digital platform and includes all companies, organisations and other elements from the platform environment, which influence the value of the platform for its participants.

Digital platform: Links two or more different groups of participants and enables value-adding interactions.

Fig. 2. Relationship between platform, platform ecosystem and platform economy [46].

Platform ecosystems or *digital business ecosystems* are a special development of ecosystems, addressing network effects. According to [143], the special purpose of an ecosystem “is the creation of a joint value proposition for the customer that a single firm cannot achieve in isolation (. . .) and which is based on complementary modules.” In the context of ecosystems, platforms proved to be essential disruptive factors which elevated some companies to the most valuable global ones. According to a survey from 2020, the seven top-ranked companies in terms of market capitalization are Apple, Microsoft, Alphabet (Google), Amazon, Facebook, Alibaba, and Tencent representing altogether more than $6.3 trillion in market value. All these companies run some kind of platform businesses [37].

1.2. Structure of the paper

PBM covers a very broad field of innovative approaches to renew and also disrupt the current and traditional businesses in designing parts and components, in machine provision and ownership as well as in order management and manufacturing itself. After a definition of the different types of platforms that are already available on the market and the various roles that are touched by PBM (Section 2), this keynote takes a deeper look into the different functions in the value chain and how they are influenced by PBM with respect to the different types of platform-related business (Section 3). We then analyze the historical developments leading to PBM taking into account the relevant results of production, computer, and management sciences (Section 4). Next, through some detailed industrial use cases, the different categories of platforms will be presented (Section 5). The scenarios show the potential for a very disruptive growth of platforms. Some questions, however, arise like: why are platforms appearing only now? Which are the challenges that may limit or delay the growth of platforms? Which are the strategical implications of the described changes? These points will be addressed in Section 6 as general challenges and opportunities of PBM, and in Section 7 which exposes strategic topics for future interdisciplinary research. Finally, Section 8 concludes the paper.

2. Categories and stakeholders of platforms

Below we give our categorization of platform types so that we can set the scope of further discussions on platforms that primarily and directly facilitate the making of products. In this narrower context, the main stakeholders of PBM are also presented.

2.1. Categorization of platforms

The categorization of platforms below is based on recent studies [26,128]and standardization definitions [189], as well as on our analysis and assessment of the different kinds of platforms related to production.

1. *Innovation Platforms* (IP) support the involvement of potential customers and users in the product and service creation process, and the collaborative development of parts, products, and services. IPs facilitate a co-creative process where both customers and suppliers are engaged and which may end up not only in shared knowledge but even in a shared ownership of the outcome [36,110].
2. *Product Platforms* (PP) offer services around the products to end-users. By making use of advanced ICT and IIoT technologies, in particular, these platforms support the realization or even the extension of targeted product functions during the whole life cycle of products (e.g., mobile phones, Tesla cars). Product platforms operate essentially in the B2C and in some cases in the B2B markets. They can monitor the use of products, diagnose continuously their operation and initiate maintenance or end-of-life activities if needed.
3. *Distribution Platforms* (DP) provide a marketplace for buyers and sellers in the specific domain of manufactured goods. These e-commerce and logistics services often embrace also the trade of tools, supplementary materials, spare parts as well as components and raw materials needed by manufacturing.
4. *Operational Platforms* (OP) offer professional software services to run production. The portfolio of these services is extremely deep and broad, including data acquisition and analytics, calculation of Key Performance Indicators (KPIs), provision of simulation, decision support, Enterprise Resource Planning (ERP), Manufacturing Execution System (MES) facilities, as well as monitoring, diagnosis and maintenance functionalities, to name only a few. These platforms offer operational services by organizing them into a multi-layered software toolbox and making them available through global cloud computing. In another context, IIoT provides such technological ecosystems to smart manufacturing which broadly overlaps operational platforms [136]. For examples, see Section 5.1.
5. *Equipment Platforms* (EP) provide also product-related services, in the form of access to capital goods in a B2B setting. These products are manufacturing assets—machines, equipment, work cells and lines, even factories— which are destined for and used in production. Along with the hardware, software services—monitoring, diagnostics, scheduling, etc.—are also typically provided. An essential element of any equipment platform is financial service which makes possible the access to, and use of, the equipment [91]. For examples, see Section 5.2.
6. *Manufacturing Platforms* (MP) act as matchmaking intermediaries between customers requiring some products and manufacturers capable of producing them. Today manufacturing platforms operate in high-mix low-volume markets, while there are more and more signs that they are getting competitive in the production of high volumes as well. Examples are discussed in Section 5.3.

The focus of this paper is set on production-related platforms whose power is in the *making*. Hence, we discuss under the concept of platform-based manufacturing the *operational, equipment* and *manufacturing* platforms (categories 4, 5, and 6 in the above list). Supporting innovation and the involvement of customers in product and service development, product platforms serving end-users and platforms facilitating purely the distribution of products (i.e., categories 1, 2, and 3 above) are only tangentially discussed in the sequel, while their relations to and possible interplay with PBM are presented in Section 7.

As emphasized already, various versions of production-related platforms are the intermediate results of an open-ended evolutionary process. Hence, the distinction and delineation between platform categories are somewhat blurred [21,58,62,75,106,115,116,182,198], while some real-life platforms operate as a combination of the above types. For instance, functions like the analysis of 3D CAD models, instant quoting, process planning, manufacturing scheduling, or predictive maintenance of machines and their components can be provided by OP both for running EP and MP services. Indeed, operational platforms give prerequisite software support for equipment platforms which run typically as a bundle of software, hardware, and financial services [43]. As will be detailed later, there is a tendency of including DP functionalities in manufacturing platforms. A product platform can assume the function of a manufacturing platform if it supports also end-of-life (EoL) activities like re- and de-manufacturing, or recycling [239] (for further details, see Section 7.3). Finally, the design of parts required in an MP can be created in collaboration with other partners using an innovation platform [36].

Variants and combinations of platforms enable the rise of new business models dealing with the provision and operation of equipment, known as equipment-as-a-service and production-as-a-service [9]. While EaaS is typically offered by machine builders in a pay-per-use scheme for single machines (or even features of machines, see Section 5), PaaS aims at operating an entire manufacturing plant by a dedicated entity which owns the equipment and is financed by third-party investors. Therefore, the borders between these categories are fluid and vary from case to case, depending on the requirements of the use cases. In Section 5 we will explain and illustrate some of the existing platforms and respective research results from recent years.

2.2. Stakeholders in platform-based manufacturing

There is already a common understanding as for the stakeholders who participate in some version of PBM [189]. We categorize those interested in platforms *for the making*, i.e., OP, EP and MP. Not all stakeholders need to be involved in a particular instance of PBM. Due to the extremely large number of variations of their interactions we deem a complete comparative study of stakeholder roles still futile.

1. The *customer* is the business partner, typically a company that needs the parts. Normally the part goes into a more complex product which is central to the business of the customer. In most cases, the customer is in charge of the design of the product. The customer has typically no direct contact with the producer since it sources products from a manufacturing platform.
2. The *producer* is operating the manufacturing equipment. This type of company does not necessarily own the machines and equipment and does not even necessarily do the fine planning and scheduling which might be provided by the technology provider but is the “supplier in charge” of the transformation of material into a part having a key role in the quality and on-time delivery of the required number of parts to the customer. For the time being, requests are satisfied by single producers. The producer can be referred to as the supplier or complementor, too.
3. The *platform operator* is an intermediary which connects customers to producers. It handles demand for products in terms of orders, selects, and assigns in some way the appropriate supplier (s) to fulfilling the order. It makes the setups, maintains the supplier network, and warrants quality control and logistics services as well.
4. The *technology provider* offers and delivers apparatus that are key to the manufacturing or assembly solution, e.g., grippers, robotics, pneumatics, sensors, etc. For these companies, the exchange of data is crucial because their business is based on the usage of their technologies.
5. The *solution provider* owns the bulk of production knowledge, as in most cases the machine builder, the system integrator, or the line builder. It provides the essential equipment for manufacturing by integrating apparatus and software. Solution providers typically offer also services to optimize the producer’s manufacturing process, e.g., by nesting for sheet metal cutting or scheduling.
6. The *IT provider* offers IT systems or services, using well-known business models such as software-as-a-service, platform-as-a-service, and infrastructure-as-a-service. It includes basic IIoT connectivity, data processing, storage, and analytics as well as cloud computing services.
7. The *owner* exercises or shares ownership of manufacturing assets. In contrast to conventional manufacturing, where producers typically own their equipment, in PBM different companies might share the ownership and the incurred financial risks. In some cases, the equipment owner is a special legal entity—a so-called special purpose vehicle— financed by large investors, like banks or insurance firms.
8. The *financial provide*r may act as a third-party investor of the manufacturing assets.

Looking at this complex mix of stakeholders and the variations of value-creating interactions among them [87] it is evident that PBM requires not only technological solutions but also new norms to build trust between the aforementioned parties, new frame conditions to secure data sovereignty and data usage, as well as new business models for financing PBM activities and for sharing benefits and risks. For these issues there are already initiatives on the way, such as the Industry 4.0 legal testbed [47], however, these issues are out of the scope of this keynote.

2.3. Use of platforms in the value-adding process

In the value-adding process of a company, there are different types of activities during the creation of a product. Usually, these activities are carried out on, and by objects of three classes: products, orders and resources. Fig. 3 highlights the most important core application services which facilitate the value-adding processes along the life cycle of products. Most of them are now included in some form of platform-based manufacturing.

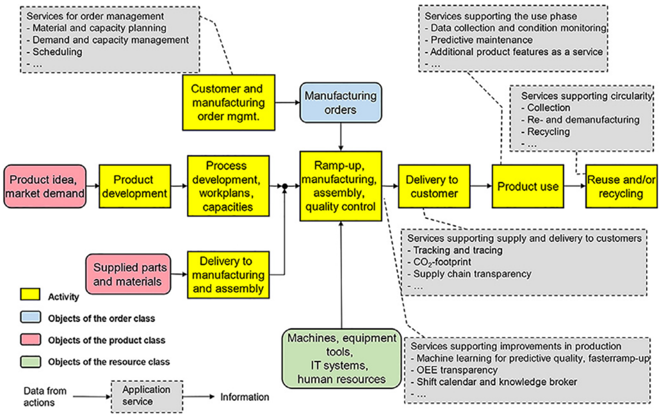


Fig. 3. Characteristic value-adding process (notation according to Integrated Enterprise Modelling IEM).

An *operational platform* makes for producers accessible a portfolio of digital services. Instead of purchasing, producers subscribe to these services and pay per use (see Fig. 4). Typical examples are monitoring the machines or their components, diagnosing their “health status”, or even providing advanced predictive maintenance support. For instance, DMG Mori’s *CELOS* [43] and Trumpf's *relayr* [195] offer such operational packages.

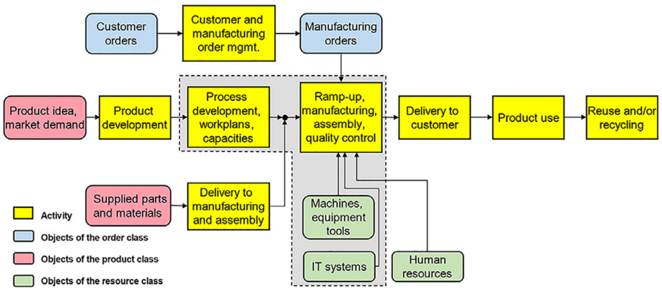


Fig. 4. Value-adding process supported by OP and EP settings (core services are included in the gray area).

The functionalities and services of OP are typically included in *equipment platforms* where the provision of hardware equipment is also part of the offer of an EP. This can be proprietarily delivered by a machine builder mainly covering their equipment. In a more general setting, for various pieces of equipment a financial provider and technology provider—a kind of system integrator—takes responsibility. Such service is provided e.g., by DMG Mori’s “PAY with Zero Risk” *PAYZR* business model [44].

While both OP and EP warrant the sufficient potential for making products, *manufacturing platforms* assume all the functions needed to meet market demand by production, such as interpretation of product models, instant quoting, automated process planning, selection of the supplier, quality control, and logistics delivery. Platforms like *Xometry* [276], *Spanflug* [220], *Up2parts* [248], and *Orderfox* [183] perform such a mode of operation. Optionally, MPs cover in some cases also production planning and scheduling as well as the supply of parts (Fig. 5).

All the described activities entail the intensive exchange of data and knowledge as depicted in Fig. 6 which shows the main activities from the aspect of an enterprise involved in PBM. Customer orders are transmitted via a manufacturing platform whereas production assets can be provided by a combination of OP and EP. Fig. 6 also illustrates

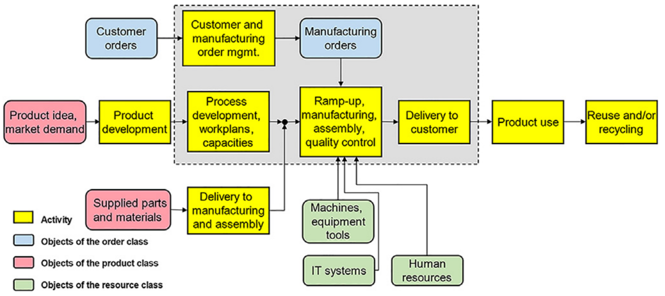


Fig. 5. Value-adding process supported MP settings (core services are included in the gray area).

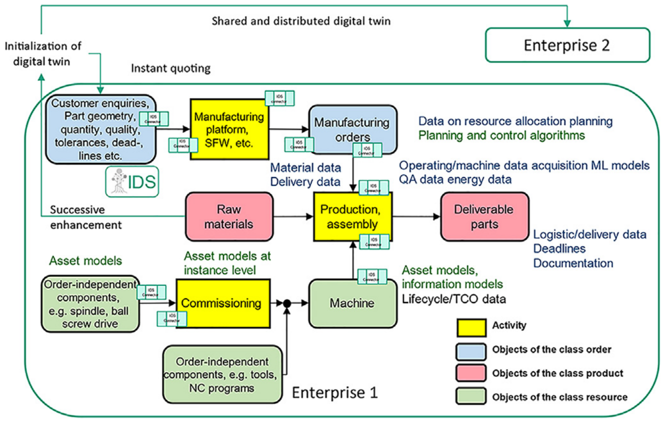


Fig. 6. Overview of a potential MP application case [205].

the points where data exchange connectors are used. This is important because, as it will be described in the following sections, platforms tend to be at the center of these exchanges and tend to acquire unique data and knowledge that makes them more and more competitive.

3. Functions in the value chain and their distribution among actors

PBM has the potential of introducing disruptive changes in the way manufacturing is realized. Before digging into the technical details, first an overview of these changes is introduced by looking at the classical way supply chains are operating. We analyze in particular the potential disruptions which were introduced by the manufacturing platforms. Finally, the bigger picture, where other types of platforms are also considered, is proposed.

3.1. Classical supply chains

In *classical supply chains*, at the physical level, companies create and assemble components. Components and subassemblies may be sourced from producers/suppliers which in turn may source sub-subassemblies from other suppliers moving from complex products down to the level of single components. Therefore, the whole supply chain is involved in the creation of a product. Materials flow from one company to the other, so the supply chain involves logistic operations as well. The concept is depicted in Fig. 7 as an upside-down tree where at the root on the top there is the OEM and each company is represented by concentric coloured circles. Each color represents a function, the manufacturing function being depicted in black and the logistic function in brown. As it can be seen, in the supply chain most of the companies involved have their black circle because they are manufacturing something which eventually will go into the final product.

However, a company in the supply chain does not only transform or move materials but executes many other activities. For instance, most companies perform quality control activities (green circle). The product must be conceived and designed (dark orange circle), therefore, especially the companies that are closer to the root of the supply chain have important product design functions that may be missing in some companies toward the leaves of the supply chain. Also, to manufacture and inspect a product, process, and inspection planning are needed as well (light orange circle). To keep the machines operational and in good shape, maintenance must be planned and performed (purple circle). The production in each company and the flows of parts in the supply chain need to be synchronized, therefore almost all the companies have to perform production planning activities (light blue circle).

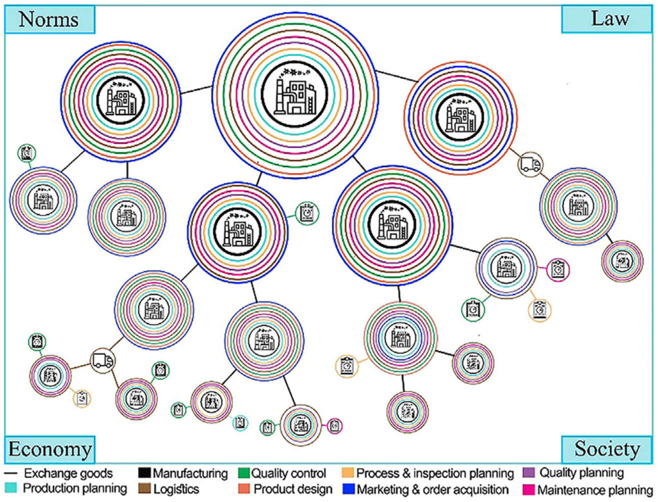


Fig. 7. Traditional supply chain.

As Fig. 7 shows, even if some of the activities may be missing in certain companies, or some activities may be outsourced (in this case the correspondingly coloured circle goes to the company supplying the activity), still, each company in the supply chain maintains many functions. Frequently, the companies toward the root are bigger and more complete in the sense that they perform internally most of the activities but generally, all the companies maintain a quite high degree of autonomy in the sense that they have a rather complete set of functions (many coloured circles in the picture). As shown in Fig. 7, all the activities of the companies need to be done in compliance with the context which means they have to satisfy norms and laws and be in equilibrium with the economy and society.

3.2. Supply chains embedding manufacturing platforms

The new concept is depicted in Fig. 8 where a new actor, the manufacturing platform, is introduced. In the figure, an MP connects the producers of parts at the bottom with the customers at the top.

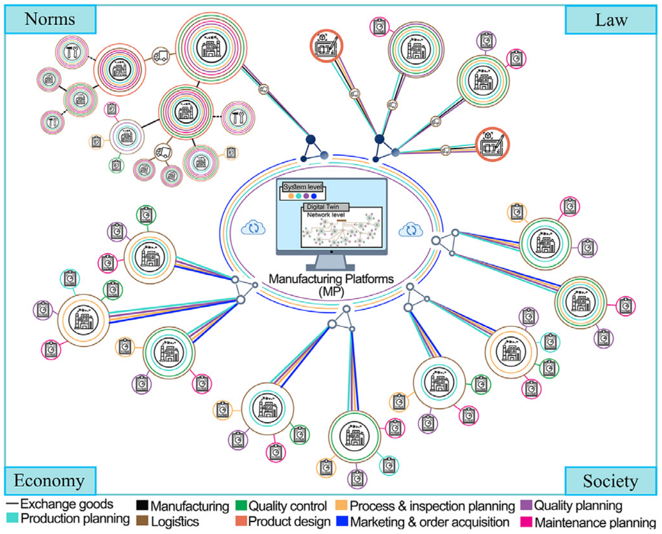


Fig. 8. Manufacturing platform.

The MP separates clients from suppliers; therefore, it changes completely the ecosystem in comparison with the situation in classical supply chains. This is the most visible effect, however, other important differences are also introduced. From the aspect of the producers, in the extreme case, a platform provides all the customers and therefore all the functions related to marketing and order acquisition are lost and substituted by the relation with the platform. Consequently, in the picture, a company instead of having a blue circle now has a blue line toward the platform. Also, a producer does not need to design parts if the design is also provided by the platform. Therefore, it loses the dark orange circle. Some platforms plan orders considering the capacity of the suppliers. In practice, they do the production planning for the suppliers which lose the light blue circle. Finally, if the platform organizes the logistics, then the supplier loses the brown circle.

On the other hand, in the extreme case, the customer may in principle concentrate on design and abandon the procurement function as well as process and inspection planning, production, quality control, and logistics functions. The resulting ecosystem is therefore based on "hollow" companies that concentrate on a few core functions and a platform that takes care of the lost functions. The panorama is of companies that are far less complete in terms of functions but on the contrary, highly specialized.

This can be visually appreciated by comparing Fig. 7 and Fig. 8. The platforms, the new "creatures", find their place in the ecosystem and deeply modify it. In the current stage of evolution, as can be seen in the top left corner of Fig. 8, classical supply chains start substituting some suppliers with platforms. However, as shown in the upper part to the right, some new companies start appearing which delegate manufacturing to platforms and just concentrate on the design the parts. This could lead in principle to the scenario depicted in Fig. 9 where a company performs design and is completely separated from manufacturing since it only dialogues with the platform. This brings to the extreme another important aspect of the structural relations in the new ecosystem. Indeed, most of the actors refer to the platform which therefore gains a central role. In particular, many direct communications between companies are lost since they flow through the platform.

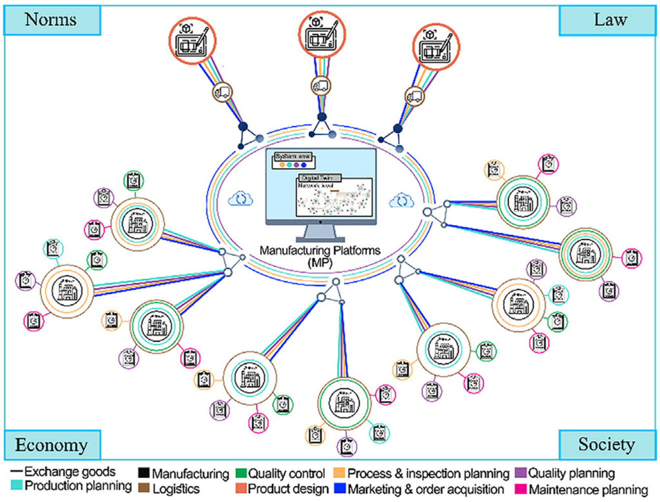


Fig. 9. Extreme case design and manufacturing completely separated.

3.3. Platform-based manufacturing scenarios

Manufacturing platforms are not the only platforms in the industrial scenario. Many other types of platforms are arising. They include *innovation, product*, and *distribution platforms*, as well as operational platforms and equipment platforms (see Section 2.1). All these platforms tend to acquire one or more of the classical company functions and perform this function for many customers (see Fig. 10). Therefore, they become more and more efficient and competitive in those functions in comparison with the traditional companies that cover many functions. As a result, they tend to grow, and their growth does not only take some space in the market but modifies their structure and the very nature of all the other companies (Fig. 10).

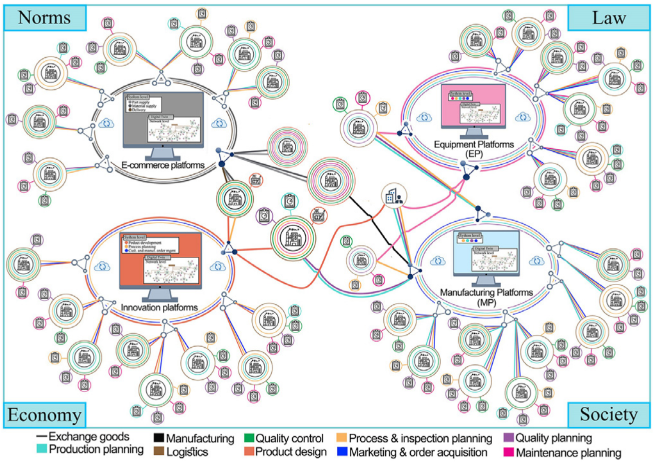


Fig. 10. Platform-based ecosystems.

Here, in addition to manufacturing platforms, also operational and equipment platforms are considered since they provide the means by which manufacturing can be carried out. Of course, these three basic categories of PBM are strongly interconnected. What EPs together with OPs may do is to provide equipment-as-a-service. Therefore, the companies do not need to acquire production capacity, but they can rent or pay per use. The advantage for the producer is very important since it does not need to invest in capital equipment and can transform investment costs into operational costs. This, in turn, makes it much easier to increase—or especially, to decrease—production capacity depending on the market conditions. Also, it makes it possible to modify the type of capacity depending on the specific production needs and quickly incorporate new technologies into the production of new or modified products. From the point of view of the producer of capital goods, there is a significant advantage in controlling each installed machine and acquiring all the data from the machine by means of Operational Platforms since the machine is not owned anymore by the producer. Hence, there is an opportunity of improving the design of the machines but at the same time, there is a great opportunity of providing additional services like maintenance or process planning by means of OPs.

Consequently, EPs tend again to prevail on previous models of buying equipment since an equipment platform makes manufacturing systems more efficient because it can rely on data and analysis carried on an extremely vast number of installed equipment over a long period and it can optimize maintenance and spare parts production. Also, EPs tend to prevail in the market over other classical equipment producers since they can take back the machines when they are not needed and give them to other users thus improving the overall efficient use of their production capacity. As a result, companies tend to transfer many of their functions to various platforms and to concentrate more and more on a few core functions. This approach changes completely the structure and the relations among the companies as can be seen comparing Figs. 7, 8, 9, and 10.

Platforms of different kinds can also make agreements and jointly offer services to the companies (wavy lines in Fig. 10). For instance, an MP and an EP may propose to a manufacturing company to take care both of the orders which will be handled by the manufacturing platforms and the machines which will be handled by the equipment platform so that the company may reduce costs and concentrate on its main feature which is its ability to produce parts. In this scenario, manufacturing platforms may become even more powerful since in principle they can combine the production capacity needs of many small companies and in this way have better deals with equipment platforms or become extremely powerful buyers having strong contractual positions over traditional equipment manufacturers.

4. Roots of platform-based manufacturing

The emergence of PBM is due to the evolution in (1) *manufacturing science and technology*, (2) *manufacturing organization and business models*, and (3) *information and communication technologies* (see Fig. 11). This evolution was not planned in any way. Therefore, the convergent process is not the result of a deliberate design, but it is the outcome of parallel developments happening in many fields with separate intents that eventually generated unexpected synergies having an impact that goes far beyond the original goals pursued in the various areas. Therefore, more than looking at a logical development that was brought to PBM it is possible to look back and analyze the roots that eventually made possible and generated PBM. As already mentioned, PBM cannot be understood simply by considering the new business model or new ICT solutions since, differently from e-commerce platforms, PBM is deeply rooted in the technology that allows making *physical parts* by using *physical machines and other resources*. Manufacturing science and technology, therefore, is at the core of PBM and the paper puts the emphasis on this area since it has been less addressed than the other areas in the existing literature. The assumption that will be discussed is that problems, potentials, and possible evolutions of PBM cannot be grasped without an in-depth analysis of what are the methodologies and tools required to transform ideas into physical products.

In Fig. 11, therefore, manufacturing science and technologies take the bigger portion and are discussed in greater detail. Nevertheless, platform-related developments in manufacturing organization and business models as well as in ICT are also presented. Various subareas are defined and for each subarea, the roots are identified and followed. However, the proposed analysis is not state-of-the-art since only the key steps that a posteriori can be seen as relevant for the realization of PBM are proposed whereas steps that may be relevant in the single discipline but have a mild effect on PBM are omitted. Each root is identified with a coloured line and is broken when a significant change, which a posteriori can be seen as relevant for the birth of PBM, is introduced. The key papers are then listed at the bottom of the line. The last changes in each root may not be incorporated in existing PBMs but they may be the drivers for the evolution of platforms and indeed are the basis for Sections 6 and 7. In Fig. 11, since for some earlier key papers, it may be difficult to get access to the original manuscript, a more recent book chapter or a survey paper explaining and referring to the old paper is introduced in the list. Therefore, the year of publication may be more recent than the period shown in the timeline. Where survey papers are mentioned, they may provide short accounts of various papers therefore their reference may appear in more than one area.

4.1. Roots of PBM in manufacturing science and technology

Since in manufacturing platforms a customer company loads a design on a platform, *Computer Aided Design* (CAD) is definitely one of the roots of PBM [153,225]. In particular, the diffusion of CAD as software tools [11] is significant and the introduction of interoperable representations of mechanical objects [12,89,92,168] is very relevant. However, a geometrical representation per se is not enough to indicate the requirements since materials and tolerances [38,63] need to be transmitted and interpreted together as well. Mass personalization has specific requirements, and only in recent years came up with solutions to the above problem [241] which, however, remains largely open (see Section 6.1.1).

Once the design and specification are known then they need to be translated into programs to be executed by the machines. Ideally, this should be done automatically; this problem however has been around for decades and is currently not yet completely solved. In particular, one of the roots is *Computer Aided Manufacturing* (CAM) [11,65,176] where process specifications for each manufacturing step (e.g., a tool path) are defined in a semiautomatic way. Another problem, however, is how to define the overall strategy to realize the part which requires *Computer Aided Process Planning* (CAPP) (e.g., the selection from alternative ways of manufacturing a part, placement of the part, sequence of operations), which is currently only partially solved [2,50,54,85,144,163,180,255,280]. Even *additive manufacturing* (AM) [5,126] that initially was proposed as a technology to automatically translate a drawing into a part needs very sophisticated process planning if conforming parts need to be realized at the first attempt. Once the part is realized, it needs to be inspected requiring the use of inspection machines which in turn need to be programmed which leads to *Computer Aided Inspection Planning* [184,283].

Research on CAPP generated the concept of *manufacturing features* which can be identified on the parts [33,64,127,131,190,216] and leads to the matching between features and manufacturing operations [107]. These concepts, even when a full-fledged CAPP is not available, allow us to find practical solutions to the problem of translating a design into machine programs, and therefore, are very relevant in PBM [240]. Operational platforms provide some of these capabilities.

Machining instructions need to be executed automatically and this requires *Computer Numerical Control* (CNC) of machines [11,55,65,194] which appeared in the 60 s, therefore, represents one of the deepest roots of PBM.

Since MPs need to realize the parts required by the customer, the system cannot be designed around the parts as it happens in manufacturing lines but rather it needs to be flexible. Therefore, flexible machines and *Flexible Manufacturing Systems* (FMS) [4,52,82,97,150,170,252] are mandatory for MP. One relatively new technology that supports MP is additive manufacturing [5,18,124,126,135] which is extremely flexible, therefore, perfectly matches the requirements of MP. The most flexible resources in a manufacturing system are obviously the operators, therefore, tight coupling and interaction between them and automated systems are extremely important in MP where humans take the lead of automation interacting with it and providing judgment and wisdom. If the machines and systems required to manufacture the part are provided by EPs, then flexibility is not sufficient and reconfigurability including *plug-and-play solutions* [119,120,152,206,209,210] is required since the machines will be used during their life by different companies having various requirements. In all cases, data collection from the machines and data fusion and elaboration are required to orchestrate the interaction of all automated equipment including robots [1,17,45,122,123,142,187,188,262,271,267,273] and automated logistic equipment. This stream was initiated with *Computer Integrated Manufacturing* (CIM) [41,57,79,134,186,217] whose concepts are currently embedded into operational platforms. Flexible automation starts appearing in also in de-manufacturing [239,268] activities which are still not considered by platforms but will represent important enabling technologies when platforms will tackle this field (see Section 7).

Automated machines need to be continuously kept in perfect operation therefore maintenance [29,160,177,230,235] needs to be introduced especially when machines are not owned by the manufacturing company. Now, it is possible thanks to sensors for real-time monitoring [74,159,203,213,269], intelligent data analysis [171] and machine learning [175], as well as model-based data elaboration to help the operator assess the real state of the machine at any given time. These features may be embedded into operational platforms.

The product realized by the manufacturing system needs to be compliant with the requirements [265]. Therefore, the area of quality and zero-defect manufacturing is very important. The same sensors and algorithms used to predict the state of the machine, used in monitoring and maintenance can be enhanced to predict the quality of the part to avoid or minimize the production of defective parts. However, after parts are made, automatic inspection using *Coordinate Measuring Machines* (CMM) [8,99,207,263] or tomography (especially for inner features produced in additive manufacturing) [28,40,125] may be very useful to analyze the product characteristics. As it will be shown in Section 6.1.4, quality is extremely important for manufacturing platforms which, therefore, owe their birth to the ability to guarantee perfect quality to their clients. Since at present MP mostly produce low volumes, quality needs to be guaranteed with flexible and versatile devices and data should be

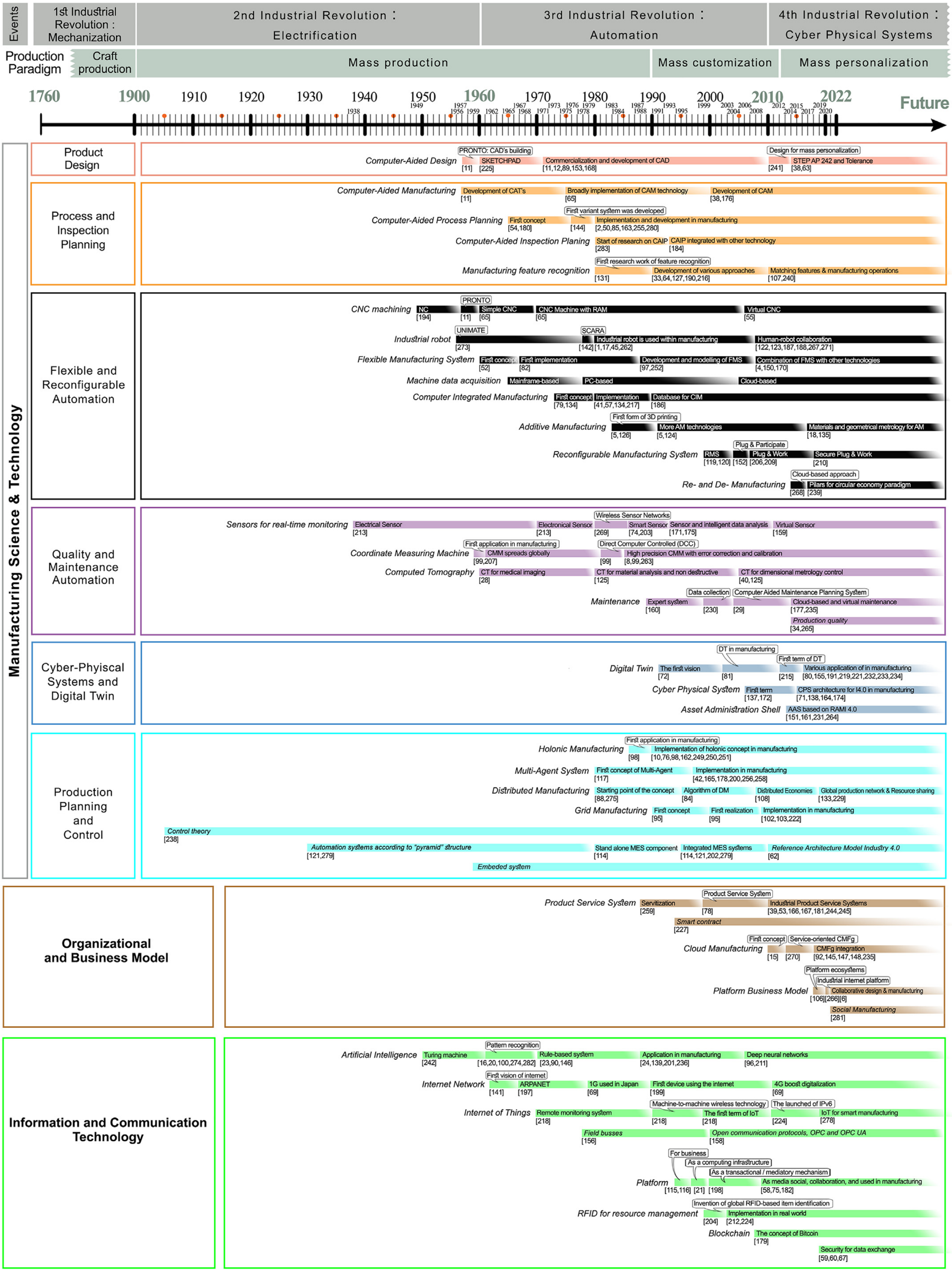


Fig. 11. Roots of platform-based manufacturing.

analyzed considering short production runs or the relation between machine state and quality. In this respect MPs benefit from a stronger integration between the maintenance and quality areas [34]. modeling plays a key role here, where *digital twins* of machine tools and manufacturing systems need to be further developed [72,80,81,155,191,215,219,221,232–234].

Platforms are essentially *distributed manufacturing systems* whose research goes back to the early days of manufacturing automation [88,114,121,202,238,279]. Such system concepts held the promise of robust, easy-to-configure, adaptable, fault-tolerant, and open manufacturing systems even before the paradigm of agent-based computing and *multi-agent systems* (MAS) appeared [42,117,165,178,200,256,258]. These were welcome because they helped realize important features like autonomy, responsiveness, redundancy, openness, and, just due to the interaction of agents, a MAS could occasionally solve problems that were beyond the limits of the capability of individual agents. However, at the same time, agent-based manufacturing systems exhibited an emergent behavior that could not be fully derived from the operation of the individual components. This was a serious impediment to the industrial take-up of MAS and led to the development of *holonic manufacturing systems* (HMS) which dynamically combined hierarchical, centralized as well as decentralized control structures [10,76,98,162,249–251]. HMS was developed into a reference architecture [253] and gained real-life applications, too. By their design, MPs are most akin to so-called *grid manufacturing systems* [95,102,103,222] which can flexibly be adapted to changing demand. Now, key ideas related to distributed manufacturing [84,108,275] are incorporated into the design and operation methods of *global production networks* [133].

4.2. Roots of PBM in organizational and business models

It was early realized that the distinction between tangible and intangible products is not clear-cut, and indeed, service permeates production, in a number of ways. Specifically, *Industrial Product-Service Systems* (IPS2) deal with dynamic interdependencies of products and services [167]. IPS2 business models can be either (1) product-oriented where suppliers provide customers with products together with some associated services, or (2) use-oriented where suppliers provide the products' service to customers through rental or leasing, or (3) result-oriented with the agreed outcome, e.g., guarantee for reconfiguration or capacity [53]. This view entailed also novel business models for manufacturing, which included new value propositions, revenue stream models as well as enterprise models capturing how to do things in the realm of manufacturing [39,78,111,166,179,181,227,259]. As for value propositions, innovation and product platforms (Section 2.1) provided essentially new ways to reach out to customers, even by involving them in a process of *value co-creation* [244,245]. Revenue streams in EssS and PaaS models facilitated doing business with less commitment (and risk) towards physical assets of production. Most developments were related to enterprise models, where even organizational changes were driven by the new opportunities provided by ICT.

In the context of manufacturing, so-called *industrial internet platforms* are essential because these provide the links between the physical and cyber components of manufacturing [235]. Hence, such ICT services are the foundations for operating industrial systems, also of operational or equipment platforms. *Cloud manufacturing* [15,92,145,147,148,270] is a broader concept encompassing an operating framework that enables also decentralized service control and management as well. Through virtualization, resources (both hardware and software) and production capabilities are captured in a computational cloud as manufacturing services that are made available for different stakeholders [92,235]. This facilitates the efficient access, integration and sharing of heterogenous and distributed manufacturing resources and in this way the on-demand production of even highly customized products. Fig. 12 depicts a typical cloud manufacturing architecture. Conjoined with a proper business model, cloud manufacturing is an enabler of PBM.

Cyber-physical system architectures are tailored to platforms that are dedicated to particular purposes. For instance, a *collaborative design and manufacturing platform* [6] consists of geographically distributed manufacturing systems operating at different locations but serving a global market. Essentially, it is a new realization of what was earlier known as the *virtual enterprise*. Assuming that all product design and manufacturing-related data can be shared and integrated, it reduces design and manufacturing ramp-up time and supports better communication between design and manufacturing compartments which has a direct positive impact on time-to-market, manufacturability, and efficiency, as well as product quality.

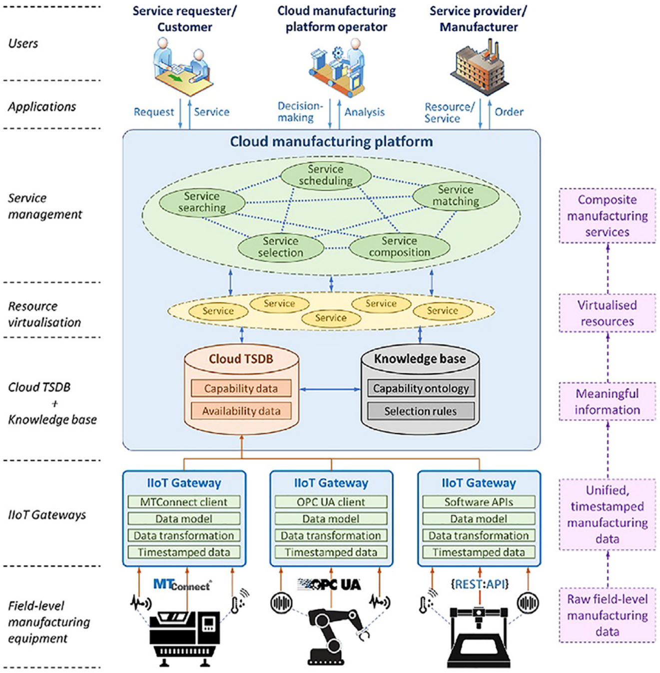


Fig. 12. Architecture of IIoT-supported cloud manufacturing [145].

Social manufacturing [281] is also a novel manufacturing paradigm for distributed, collaborative, service-oriented and customized production. Again, this concept builds on cloud manufacturing services [266]. Social manufacturing makes available and integrates the use of heterogeneous manufacturing resources, even among geographically distributed enterprises. These resources may include CNC machine tools, machining centers, robotic manipulators and most typically, equipment for additive manufacturing. The novelty is that it facilitates the communication, coordination and flexible (re-)configuration of manufacturing resources via *social media*. Manufacturers merely need to concentrate on their core business and share some non-core business tasks with other enterprises in the form of outsourcing and crowdsourcing. Whenever the manufacturing of customized complex products requires the use of a variety of high-end manufacturing equipment, participating enterprises may share their appropriate resources and realize the production in collaboration. As it is expected, it can quickly respond even to individual consumer demand, while improving resource utilization and reducing costs and participants can achieve win-win goals. Note that while social manufacturing defines the essential channels for sharing information and resources (see also Fig. 13), it does not account for a business model which could make production profitable in the long run in such a setting.

4.3. Roots of PBM in information and communication technologies

In the 1990s the concept of *Computer Integrated Manufacturing* was a major issue in R&D and industry. Companies modelled their business processes in administration and manufacturing, later they introduced ICT tools to support their planning and scheduling, allow machine data acquisition and other production-related functionalities. However, the computing power was limited, and data storage

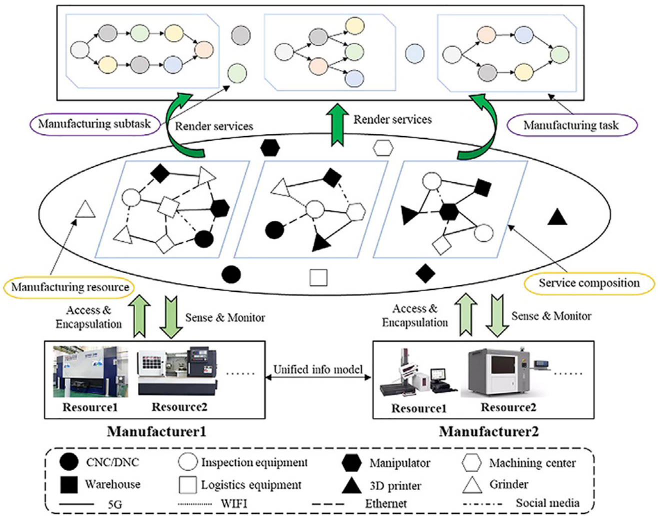


Fig. 13. The organizational logic of social manufacturing [281].

was still expensive. This situation changed with the improvements in microelectronics, embedded systems and smart devices that were implemented directly into mechanical components. In 2012 the Acatech study “Agenda CPS” laid the foundation of Industry 4.0 [71]. The study already described that cyber-physical systems (CPS) penetrate different domains; besides manufacturing, these are smart mobility, healthcare, and smart grids. It even described the necessity of new types of software services, architectures and required infrastructure to run the services and collect the data from CPS. By definition, CPS communicate and interact with each other, make use of available data and services, and offer new types of functionalities, services and properties. As they address the domains mentioned above, interoperability and platforms are key to the use of CPS efficiently [137,138,156].

It is evident that physical devices that are equipped with embedded systems require identification and even localization to track and trace them during their supply chain. As CPS use internet technologies to connect and communicate [164] their environment was soon called the *Internet of Things* (IoT) [69,141,197,199,204,212,218,224,278].

During the time of CIM, there also existed systems that tried to capture the knowledge and experience of machine operators, making it available to a larger community inside an organization: we used to call them expert systems. From today’s point of view, these systems were the first applications of artificial intelligence [16,20,23,24,90,100,139,146,201,236,242,274,282], technologies that are popular today [96,211].

In recent years, ICT has developed powerful tools to support manufacturing and data exchange between the different parties in the ecosystems mentioned above. To secure data sovereignty the GAIA-X initiative has been proposed to provide rules, data governance and a reference architecture for data exchange and data sharing within platform ecosystems [59,60,67]. The objectives of GAIA-X for the production domain include the protection against disruptive threats posed by central data collectors such as manufacturing platforms and the creation of rules ensuring that every participant retains sovereignty over their sensitive data respective to their intellectual property. The reference architecture includes services to allow trusted access to different types of data spaces representing entire industries, branches, scenarios or business segments. Data spaces are based on semantic descriptions and thus on semantic interoperability. They store data at the source of its origin, e.g., factories, lines, machines or even components and, by the use of connectors, guarantee its transfer, access and computing for defined and limited users, their business applications and use cases. The more data sources, users and business applications exist, the livelier becomes the platform ecosystem.

5. Industrial examples of platform-based manufacturing

In the following subsections, we describe some industrial examples of platforms that are already in use. From among the operational and equipment platforms, for an in-depth analysis we selected *CELOS* which warrants generic interoperability of different vendors’ equipment, as well as *Relayr*, which introduced a novel, complex business model. We focused on the currently largest MP, *Xometry*, and also on *Spanflug*, which provides a benchmark for interpreting product design information for the whole industry. The analysis is based on public company materials and interviews with leading company representatives. These examples illustrate that the borders between the categories mentioned above are somewhat fluent according to the business model and the market of these platforms, but the basic archetypes discussed earlier can be easily mapped to real cases.

5.1. Examples of operational platforms

Operational platforms have been on the market for some years now; some of them have started with manufacturing execution system functions, some of them with pure IIoT functions, such as data collection and analytics of sensor data, offering today such services as predictive maintenance, predictive quality and others. The first ambitious initiators were multi-technology companies like Bosch and Siemens covering the whole spectrum of CPPS. While the first attempted to host all its data processing and storage services on its own cloud infrastructure, the latter—with its *MindSphere* platform—relied rather on dominant global cloud suppliers like Amazon and Microsoft. In retrospect, this solution proved to be more competitive and viable, even though reduced the value capture of the company in the whole ecosystem and exposed the platform users to risks related to data sovereignty. Another big player, SAP, coming from the enterprise IT business attempted to create its own complete industrial OP (called Leonardo) but afterwards, having limited success, retracted in 2020. Here, the critical issue was the lack of sufficiently refined technical support in the access to, and control of physical devices and equipment [136].

A number of machine builders have started to develop proprietary *software services* for their machines and equipment. In 2013, DMG Mori was one of the first to offer a “family” of services called CELOS which supported machine operators through the entire life cycle of their parts to be produced, from visual programming through NC simulation up to improving the machines’ operation. Services around the hardware, whether it is machines or components, have become also common (Fig. 14). CELOS guarantees that the connected machines provide various signals on their state, parts counter, or the part program just executed. For processing the stream of incoming data, it offers open application protocol interfaces (APIs) to CAD-, CAM or MES systems. It is open to third-party products as well [43]. Some other companies now also provide their own platforms that run similar services, offering also functionalities that carry out tasks related to more than one machine, even to entire factories [128].

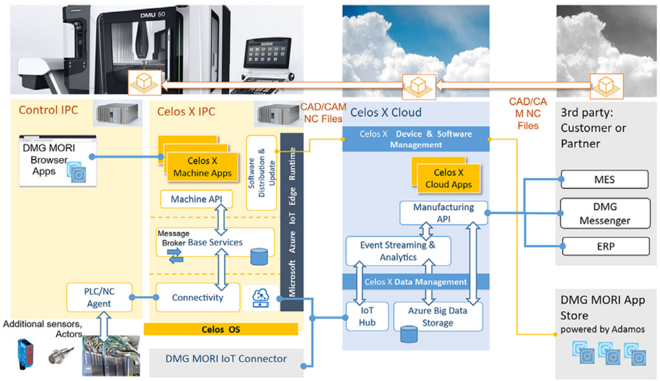


Fig. 14. Overview of the he CELOS system (source: DMG Mori).

Unfortunately, proprietary OPs suffered from some disadvantages:

- Neither the platforms nor their proprietary services are interoperable, hence manufacturers that run machines from different vendors have to deal with several platforms. Even if most of these proprietary platforms are able to integrate machines of other vendors, these legacy machines cannot use all the services available for their own machine portfolio.
- Lacking “critical mass” at the level of cloud services they cannot compete with global, multi-national tech giants.

A notable exception is the *Adamos* IIoT platform which has been launched in Germany in 2017 in the cooperation of four (by now six) machine builder companies, a leading software company in enterprise information technologies (EIT) and a consultancy firm. Adamos has a broad portfolio of IIoT services, including device connectivity, as well as numerous backend and frontend applications [136]. The offer of services is *open* to external application developers, the so-called complementors, and Adamos does not give preference to any of them, hence it is *neutral*. The data model of Adamos supports different types of standards, e.g., for connectivity MTConnect, or in the domain of injection moulding the so-called EUROMAP recommendations. While the backend services are controlled by the EIT specialist, the fundamental cloud infrastructure is provided by the generic Azure cloud. Now CELOS functionalities either run on Azure or through the Adamos IIoT platform.

5.2. Examples of equipment platforms

Equipment platforms provide the operating architecture for new types of business models, like for instance EaaS. Today EaaS is used in many different branches such as office equipment (printers, copiers), facilities (air compressors), aerospace (jet engines), agriculture (farming equipment) and recently also in manufacturing (machine tools, robots) [22]. In an EaaS business model the revenue model is completely different from the build-sell business model since the manufacturing equipment or even whole production systems and factories are no longer sold. Machine builders or equipment suppliers provide the machines for a fee, typically oriented to availability, time of usage or output. When the fee is calculated based on the time when the machine is available, then the Availability Guarantee business model is used. When the fee is calculated in terms of the output, the PaaS business model is applied. From the viewpoint of the producer (i.e., the user of the machine tools) these business models substitute capital expenditures (CAPEX) by operating expenditures (OPEX). Instead of buying a tangible product like a machine, the producer pays for the machine usage, its output and thus for its availability or performance.

In all these business models, the solution provider (e.g. the machine tool builder) is in charge of the equipment availability and thus also of maintenance, overhaul, and replacement support therefore all these new business models require the operating architecture provided by the EPs. Equipment platforms are based on a close and continuous contact of the solution provider with the producer. The solution provider is forced to improve the overall equipment effectiveness (OEE) through online access to the machines, advanced analytics supported by machine learning and additional services offered to the machine's users [19,234] like condition monitoring, predictive maintenance, operator training, performance optimization.

From the *financial point of view*, solution providers used to sell their machines and normally they were covering most of the expenses to build the machine with the upfront payments while making their profit with the final payments, therefore, operating most of the time in positive or mildly negative cash flow. In contrast, the *revenue model* of these new business models provides a permanent financial flow [19] but entails a bigger financial exposure for the solution provider. To cover the financial burden, in some cases, the EP business is bundled by financial provider or a “special purpose vehicle”, a legal entity that owns the production assets and is responsible for the financial transactions, interacting both with the producer and the user of the assets.

For example, among the first movers into this new business model in Europe, DMG Mori has launched its equipment platform named PAYZR (PAY with Zero Risk) and, in parallel, the new machine model M1 in the segment of universal three axes milling (see Fig. 15). Already after some months, the market share for EaaS for this machine was significantly high, together with the new customer ratio compared to conventional transactional sales. With the EaaS offer, DMG Mori provides its machines as a service within a combination of subscription and pay-per-use. The monthly base fee includes the all-around carefree package covering transport, setup and commissioning, training, maintenance, and spare parts as well as insurance for machine breakdown and revenue. Additionally, the producer is paying a usage fee based on the spindle hours. Producers have no investment risk, no down payment, and no obligation for a minimum usage of spindle hours. Short contract terms of 12, 24 and 36 months are applied as well as the freedom of choice at the end of a contract by having the possibility to return the machine, buy it or extend the contract. DMG Mori Finance, a legal entity inside the corporation owns the machine and charges the subscription fee. This legal entity is controlled by the German Federal Financial Supervisory Authority (BaFin). Producers adopting PAYZR are using all required services from DMG Mori instead of those from third parties, e.g. specialized companies for the refurbishment of spindles. Through the focus on high OEE of EaaS machines, DMG Mori Digital is monitoring the connectivity and availability of the machines and thus the firm is able to control the installed machines and in various cases to increase the output of the machines.

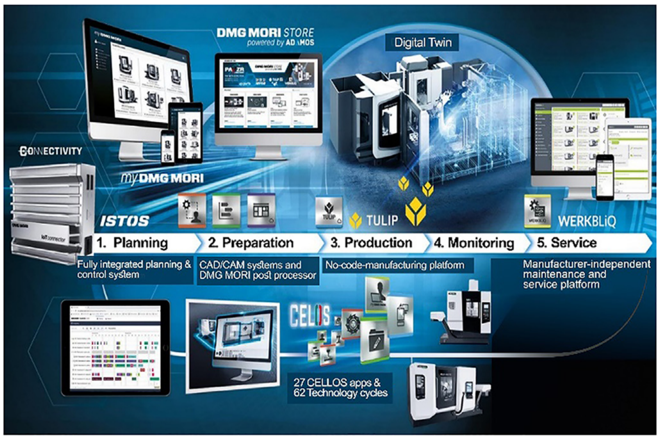


Fig. 15. The Pay-with-Zero-Risk platform (source: DMG Mori).

Another early mover with first-hand experience in the EP business is Trumpf. In contrast to the above case study, *Trumpf* machines are owned by MunichRe, an insurance company, and monitored by *Relayr*, a firm that uses its own platform and services to connect and access the machines' data. Trumpf even conducts the nesting and scheduling of manufacturing orders for the producing companies. Producers may be either companies that need sheet metal parts for their products, or firms that offer sheet metal cutting and forming services as contract manufacturers. The increase in OEE is monetized and shared between the producer, Realyr and Trumpf. In the two case studies from DMG Mori and Trumpf, representatives of the companies emphasized that data access and monitoring of components are essential for increasing OEE and warranting the economic success of EPs.

One further step toward the more efficient use of resources is the adoption of the PaaS business model at the *factory level*. This concept has been established by *FlexFactory*, a joint venture of Munich *Re*, Porsche and MHP. Its main goal is to share the risks of capacity usage of a factory and its financial structure by using external capital and to manage pricing and billing [104]. Since production facilities can be used for mass production from different customers there is a higher degree of flexibility in manufacturing equipment and material flow installations. By the use of EP it ensures maximum availability of manufacturing capacities for different customers. Examples for realized projects are the smart press shop in Halle (Germany) where Porsche and Bentley sheet metal parts are produced and Volkswagen Osnabrück (Germany).

5.3. Examples of manufacturing platforms

5.3.1. Manufacturing platforms in action

Today, various *manufacturing platforms* have established themselves in the market, offering the production of parts-as-a-service – usually still in the form of NC chip-making, 3D printing or sheet metal production. Manufacturers can join these platforms by offering their resources and thus their production capacities while the platform carries out all order management activities. Based on the product data (typically a 3D CAD model, or a STEP file) provided by the customer, the MP automatically and immediately calculates the price and the delivery date and assigns the manufacturing order to one of the participating factories. The assignment is either directly controlled by the platform operator, or alternatively, it facilitates a negotiation during which the best manufacturer is selected. Thus, end customers do not have direct contact with the manufacturers anymore, they only access the platform. In addition, the platform manages quality control and the entire logistics. Automated process planning and offline machine or robot programming are optional offers of some MPs. Such faculties are extensively supported using *digital twins* (DTs) [232,233]. Should a manufacturer need capacity expansion, then even the investment in these expansions may in some cases be supported by the platform.

There are several commercial manufacturing platforms on the market which is still pretty wild with big differences in terms of price and quality. The leading MPs, such as *Xometry*, a US-based platform founded in 2013, are already covering 20 different technology-specific processes including surface treatments. Xometry provides the transport of parts from the producer to the customer and, in the USA, also the transport of materials to the producers. Now, Xometry manages a network of more than 5000 official producers worldwide some of them operating different plants [276]. Some of these producers work exclusively with Xometry and withdrew from traditional supply networks.

To ensure manufacturing quality, new producers are expected to manufacture sample parts from Xometry's test parts. Once a producer is listed as a manufacturing partner, there is an internal rating considering the time and reliability of delivery, communication with the Xometry team, transport performance and quality of the parts. Rating is asymmetric: the producer knows the rating, but not the customer. For the producers, the participation in the platform is useful since it gives access to a wider segment of customers and also manages the relationship with those. Also, for a highly ranked producer, it can guarantee advance payment, a form of financial provisions. In addition, it can provide financial assistance to support manufacturing capacity expansion together with special deals with machine tool builders due to their commercial power. Some bigger clients buying big quantities require that Xometry includes in the onboarding process their traditional suppliers as manufacturing partners. For repeated orders in general and especially for traditional supplies incorporated in the platform, Xometry tends to maintain the same producers to foster trust building.

One of the assets of Xometry is the AI-based *quotation engine* which was started in 2019. This engine is based on the cumulated set of transactions, therefore given the time the engine has been already operating and the business dimension of the company, it can become an entry barrier for potential competing MPs since new actors cannot have access to the same cumulated knowledge. On the other hand, from the side of the client, knowledge is protected through non-disclosure agreements (NDAs) which are normally tighter than those signed by companies with their suppliers.

For special purposes, Xometry also runs a *quality inspection* in Munich. Functionalities like tracking and tracing parts are also possible but must be pre-agreed in advance. Unlike other platforms, Xometry offers not only manufacturing but also assembly of parts; however, assembly is not the regular case as, in contrast to parts manufacturing, here quoting requires intensive human interaction. In Europe the platform cooperates directly with its producers, while in the U.S. it runs its own assembly shop.

To accelerate its growth, Xometry has recently acquired Thomasnet, a US- based industrial sourcing platform, to offer not only manufacturing but also materials, chemicals, IT solutions and other goods required in the B2B business. Hence, it assumes also the functions of a *distribution platform* (see Section 2.1). Recently Xometry also bought a company producing process planning software for sheet metal forming.

Spanflug, Up2parts or *Daedalus* are start-ups, each of them connected to their chip-making factory. These platforms have started automating the quoting process for their factories' customers. Other companies are Proto Labs (US), offering also injection moulding parts, or Haizol, China's leading manufacturing platform. For some comparison, see also [247].

Spanflug was founded in 2018 by two engineers taking their PhD from the Technical University of Munich. They started their own business based on a deep understanding of CAD files, feature information and the interpretation of technical drawings. Technological excellence in design intent interpretation and process planning resulted in a powerful tool for instant quoting. In the beginning, this Spanflug tool was connected directly with a family-owned manufacturing company. Today the platform manages a network of app. 150 manufacturing partners in Germany, Austria and Switzerland. Their software products include a WebShop, mainly consisting of instant quoting: after the customers upload product-related drawings as pdf and STEP files and choose the material, the platform analyses the input, extracts material and fitting information, part treatment, surface information and – if available – also the specification of tolerances. The analysis also includes text extraction, Optical Character Recognition (OCR) and extraction of further data from pictures. The analysis results are the price and the delivery date, generated completely unsupervised, for in many cases the users only have a low-level technological background. Next, the WebShop platform assigns the orders to appropriate manufacturing partners. Requirements towards the partners are not only related to technological capabilities but also to compliance with software tools and participation in an internal ranking.

5.3.2. Reference architecture for manufacturing platforms

Catena-X is a project that has been initiated by some major German companies—original equipment manufacturers and suppliers—and aims at building a digital ecosystem for the German automotive industry and its supplier network [30]. The entire project consists of three major building blocks:

- The "*workbench*", which is a research and development project funded by the Federal Ministry of Economic Affairs and Climate Action. 28 partners from industry and academia work in several sub-projects on IT architectures for the data-sovereign exchange of information through the entire supply chain, using services and applications typically needed by the automotive industry. One of the sub-projects deals with the development of a reference architecture for manufacturing platforms.
- The Catena-X Association provides *guidelines* and compliance rules for its members from the entire automotive network, works on standardization and transfers results from the workbench to the industry.
- Some operating companies oversee running and updating the infrastructure for the *digital ecosystem*. The infrastructure is based on GAIA-X (see Section 4.3). The operating companies also offer Catena-X services and applications to others who deliver components, parts, software, or services to the automotive industry.

A sub-project of the workbench develops a *reference architecture* for MPs based on GAIA-X-rules [48] warranting data sovereignty as well as applications and software services mainly to ensure that data ownership, access and usage control stay at those partners of the network who have originated the data, e.g., from their machines, lines or factories. Today, an MP is mainly used for small lot sizes, but the partners in Catena-X develop their solutions also for larger, automotive-typical order sizes.

The goal of *Smart Factory Web* (SFW) is to provide an independent open architecture technology for marketplaces that offer manufacturing capacities. It is an official testbed of the Industrial Internet

Consortium and a platform to split manufacturing orders to shared capacities of smart factories that are registered on the platform [247]. The platform connects the different stakeholders of industrial marketplaces. SFW aims at improving the value chain by flexibly equalizing the capacities between the participating smart factories. To this end, the factories register with the SFW portal, allowing customers to find appropriate production capacities. By now, SFW even provides features to support the management of supply chains and networks. Since manufacturers usually depend on suppliers and are distributed across several sites, this functionality is a step towards enabling negotiations across enterprises and organizations. One of the main aspects of SFW is its open approach relying upon international standards, e.g., for the modeling description of assets or the use of standardized connectors between the participants based on principles of the International Data Spaces Association (IDSA) and GAIA-X [94].

6. Challenges and opportunities of platform-based manufacturing

The introduction of various forms of PBM evoked a sharp disruption in the field of mechanical part manufacturing. While during the formation of MP, EP and OP, some good combinations of features, as described in Section 4 proved to be an instant then lasting success, we must emphasize that there is “no free lunch” in PBM either. To grow and become really successful, platforms have to face important challenges. Some of these challenges are in the value-adding processes described in Section 2 and are analysed in detail in Section 6.1 as challenges for manufacturing science and technology. Other challenges are more pervasive as they are related to organisational and business models, as well as to ICT, described in Section 6.2 and 6.3, respectively.

The evolutionary interplay of manufacturing and information sciences and technologies, along with the advent of innovative business models opens new opportunities as well. What makes PBM different from more traditional settings of manufacturing is a new distribution of data, information, knowledge, authority, and after all, responsibility. While related analysis and foresight on the role of platforms focus rather on current issues of ICT [266], as well as on the organizational and business issues [27,136,226], in what follows we put the emphasis on the engineering challenges and opportunities of PBM. Even if the various issues are addressed separately, it is quite clear that problems are strongly interconnected and cannot be solved by a single player or academia alone. Also, platforms are grown up from practice not from theoretical development therefore the way the various improvement needed can be synchronized is in itself a matter that requires new approaches.

6.1. Challenges for manufacturing science and technology

6.1.1. Design intent interpretation

In the case of MPs the value-adding production process starts with the interpretation of the design intent and expressing it in terms of production tasks which, if executed by means of the available production resources, result in the intended product. Both instant quoting and process planning (see next subsections) depart from this information. The main challenges are as follows:

- Products are specified by various kinds of documents, like 3D product models, STEP files, drawings, tables, and textual documentation. Some representations contain already technology-related information, such as assembly graphs, while more often only a bill of material (BOM) is given which needs further interpretation.
- Dimensioning and tolerance specifications are typically graphical and textual since standard CAD systems do not have capabilities for transmitting such information.
- The set of available production technologies and assets defines the context for interpretation. Given the different technological backgrounds, the analysis of design documentation may result in different specifications of production tasks as well.
- The implications in terms of processing the parts, like the cost of producing parts with those tolerances and the risk of producing scrap need to be estimated.

Platform-based manufacturing, and in particular MPs resolve the above issues by modeling the manufacturing assets of their suppliers in a uniform, if possible standard way, thereby creating also a stable and single context for the design interpretation (for details, see Section 6.3.1). As for giving product-related information, MPs can take two distinct approaches:

- The input language for specifying the product can be constrained. Thereby the MP has a standard interface towards its customers which alleviates interpretation efforts. Notwithstanding, this solution makes a barrier towards the customers by restricting the kinds of products to be delivered by the MP and by requiring the customers to express their needs in terms of the platform’s language. A large customer and supplier base, interested in the production of conventional products is an opportunity to standardize the input of MPs in this way.
- The platform can be inclusive by accepting product specifications in any format the customer is able to provide. In this case, the platform has to invest efforts into the automatic interpretation and consolidation of these documents, and in the last resort, may call for human involvement as well. Larger MPs with massively many transactions have an alternative opportunity also here: they can employ advanced machine learning techniques for solving the interpretation problem (see Section 7.1).

In both scenarios, the pragmatic concept of manufacturing (and assembly) *features* can provide the basis for capturing design intent in a way which can be passed to manufacturing [32]. Features that originated in the pre-computer era of manufacturing are now taken as the key to interoperability across heterogeneous domains [140]. Research in functional feature modeling can help in representing every facet of product designs, notably related to function, structure (including geometry) and expected behavior. For instance, one of the most complete feature models to date represents in an integrated way the (1) explicit intent of the designer, the (2) physical structure and (3) the physical phenomena which realize together the intended function. Fig. 16 shows how a product model can be decomposed in this way, while maintaining the relationships between the three aspects.

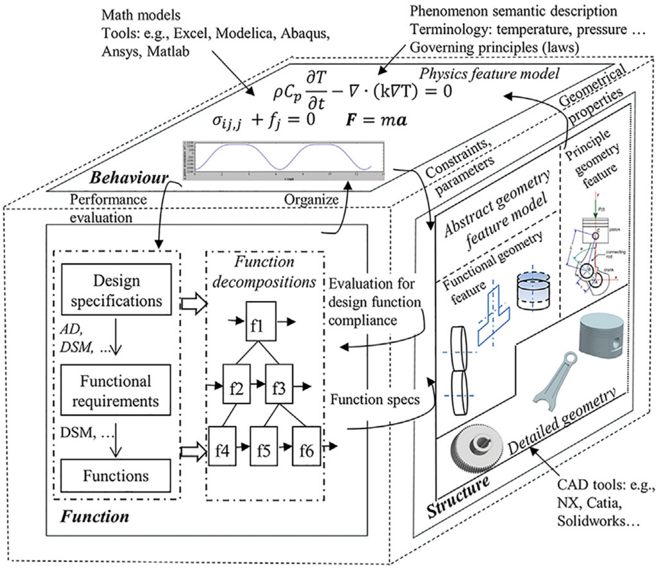


Fig. 16. Multi-faceted functional feature modeling [32].

Some MPs allow for uploading along with digitalized product models also engineering drawings which contain information about the dimensioning, tolerance, measurements and associated regulatory (like ISO or DIN) standards [220]. These pieces of information are of primary importance not only for instant quoting (Section 6.1.2), process planning (Section 6.1.3) and production but also for quality control (Section 6.1.4).

The appropriate graphical elements and symbols should be recognized, and their relationships with the digital CAD model of the product have to be established [208]. A conceptually similar problem is generating an assembly task sequence graph from manual assembly instructions [214]. It is an additional challenge if this extraction process should cover also tables, notes, and textual descriptions, as discussed in [254]. This complex interpretation problem calls for the combination of advanced AI techniques supporting optical character recognition, text processing, clustering, and classification of visual information – all of which imply some form of machine learning (see also Section 7.1) and semantic modeling.

6.1.2. *Instant quoting*

One of the most important challenges for a platform is to provide fast or even *instant quotations.* Quotations are at the core of the revenue model of platforms since if a quotation is too high the customer may be lost but if it is too low the platform may lose money. The time to submit the quotation to a potential client is also a sensitive issue in the value proposition of the platform. Unfortunately, calculating quotations is a very complex problem since the cost of the part depends on the specifications and on all the activities required to obtain it. Considering how quotation may be done by a platform there are two dimensions to be considered: centralized vs. distributed and analytic vs. synthetic.

In *distributed quotation* the platform asks potential suppliers for quotations and then it selects the best one. This requires a prompt response from the suppliers which must dedicate effort to be able to give the answer; the effort is actually multiplied because each supplier has to do the quotation. In this case therefore the total cost for quotations is actually bigger than in traditional supply chains and the pressure is higher, leading to a potential a weak point for platforms. In a *centralized quotation*, on the contrary, it is the platform that does the calculation, and the supplier just has to decide whether to accept to manufacture a pre-quoted order. In this case the knowledge to do the quotation must be acquired by the platform, not a simple task given the variety in the technologies, materials, part shapes.

On the one side, quotation performed *analytically* means that the process is explicitly defined and the cost of the various operations and the material are calculated analytically. If done manually, it requires a significant effort. The challenge would be to do it automatically, however, at the moment tools able to define the process in detail and do the calculation are still not available since the formalisation and use of knowledge in this field is still largely a research area. On the other side, *synthetic calculation* is based on similarity with parts and features already done in the past and therefore it is calculated without considering in detail the technology but considering a series of inputs that are then transformed in some way into an economic value. Explanation of why certain results are obtained is not easy and accuracy may be lower than with analytical approaches.

In both analytic and synthetic calculation, a precise quotation heavily relies on the specifications (e.g., tolerances) already discussed in Section 6.1.1. To address this challenge two approaches are followed by manufacturing platforms. (1) On the one hand, some platforms create a first centralized quotation without considering tolerances and ask the producers to propose in a distributed way their quotation based on the whole set of data available (including possibly tolerances) even if not provided in a structured format. (2) On the other hand, other platforms such as Spanflug, are trying to create more sophisticated interfaces to be able to acquire all the information in a structured way and be able to consider all the aspects in the (instant) quotation. This second approach involves quite complex technical issues and requires an in-depth analysis of each type of technology used in the production of parts. Therefore, the way tolerances are specified and manipulated during quotation is becoming a differentiating factor among platforms and will probably affect their evolution with some platforms remaining more generalist and others that will become more and more technical.

In quotation, AI in general, and learning in particular, represent an important opportunity since these methods may improve the capabilities of the platforms or the suppliers to define precise quotations quickly (see Section 7.1). This issue may become a key competitive element, especially in centralized synthetics approaches, since a platform which starts growing tends to acquire more and more knowledge from processed orders increasing the ability of performing precise quotations. This may eventually lead to the concentration in the market of platforms.

6.1.3. *Automated process planning and NC programming*

Platforms are offering a wide spectrum of technologies which includes material removal processes, sheet metal forming technologies, additive manufacturing, electrical discharge machining (EDM), laser cutting and welding, etc. Some platforms focus on one technology while others are generalist and tend to cover more and more technologies. Some platforms specialize in a given set of materials while others are able to cope with any kind of material. Nowadays most of the platforms deal with single parts and have very limited capabilities for dealing with assembled parts. Production of more complex parts with a BOM is indeed one of the open issues at the forefront of current developments.

Departing from a model of products (which captures design intent) and the specification of available technologies and resources of production, it is *process planning* which generates plans for realizing the products in a given production environment. The process plans should comply with all relevant *constraints* of the product, the actual technology, and the resource base (machines, fixtures, tools, human/robot operators) [54]. The origin of most of these constraints is technological and geometrical. However, in process planning one has to resolve an epistemological and a computational dilemma: it cannot be warranted that the available domain knowledge is either complete or consistent, and the computational complexity of CAPP in any realistic formulation is notoriously high. Incompleteness is especially an issue in PBM where information about the product resides at the platform operator, while detailed knowledge of resources lies at the producer, and the parties have no completely shared models of either. *Features* (see also Section 6.1.1) which define "small worlds" of manufacturing are prevalent in every domain, such as machining, additive manufacturing, bending, welding or mechanical (dis)assembly. However, any feature-based model is only a single interpretation of the design intent, where features are taken out of the context of the overall planning problem. When put together, local pieces of the plan can get easily into conflict resulting in an over-constrained planning problem.

Now PBM provides a new opportunity to resolve the above challenges of CAPP (see also Fig. 17):

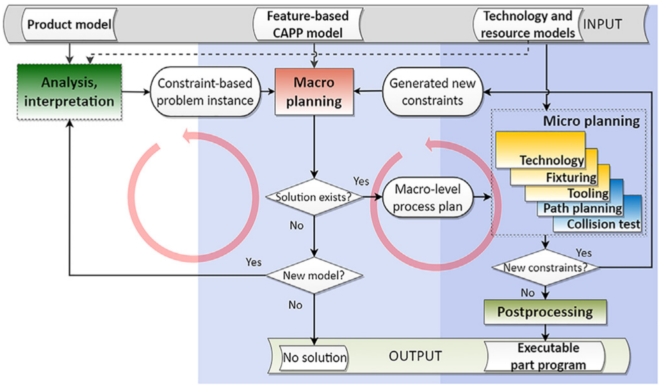


Fig. 17. Generic constraint-based CAPP model (adapted from [113]).

1. *Analysis and interpretation* of the design intent results in a feature-based model where the tasks, resource alternatives and constraints on resource assignments and task precedences are defined. If this model is under-constrained then missing pieces can be added later, by micro planning.
2. At *macro planning*, a solution can be generated that satisfies the constraints and is (close to) optimal according to some criteria, like the number of setups or other changeovers, the estimated total production time or cost, etc. Whenever it fails to find a

solution, planning should be resumed with a new feature-based interpretation of the product.

3. At *micro planning*, specialized expert modules check the macro plan from various aspects like tooling, fixturing, path planning, etc. In case of infeasibility, micro planners generate new constraints and feed them back to macro planning which is resumed. This cycle should be done iteratively until a completely feasible plan is found.
4. Finally, at *postprocessing*, NC and/or robot programs are generated automatically.

In manufacturing platforms, steps 1 and 2 of the above planning workflow are to be executed by the platform operator, leaving the two subsequent steps to the producer. This decomposition facilitates making better-informed decisions in instant quoting, too. When producers are using expensive machinery such as laser cutting or welding equipment whose optimized programming requires special experience, then the whole workflow can be executed by the platform operator. In this case, together with the customer order, completely specified part programs are also communicated with the producers. Equipment platforms can also populate the portfolio of services accompanying their hardware with such CAPP functions.

An alternative option is returning to the principle of the so-called *variant process planning* [50] which predates any computer-assisted planning methods. This similarity-based method recalls and adapts process plans of earlier products whose geometry, properties and features are close to the actual product at hand and were produced in a similar environment. Group technology was used to cluster and generalize products of similar features, and to characterize their production requirements in terms of standard plans. This approach, because of the difficulties of automated adaptation and its lack of optimization, did not gain much ground in contemporary CAPP systems. However, applying modern similarity-based machine learning methods in PBM may open new opportunities and turn this trend to the opposite: for feeding these data-intensive methods, the centralized platform operator can set up and continuously update and extend a dataset of product specifications and corresponding process plans. If the platform operator is able to fine-tune particularly the initial set of plans (or can invite its producers to do so), then, as a kind of bootstrapping, variant planning can also be made operational.

6.1.4. Quality control

Platforms must guarantee that the produced parts satisfy the specifications, including geometrical tolerances and material properties. Once the part is produced the problem is to assess the compliance of the produced parts. This is a very challenging and vital task for the platforms since platform reputation is heavily dependent on quality. Different ways can be adopted to answer this problem:

- Let the *suppliers measure* the parts produced and let they take care of the quality; obviously, since the customer does not see the suppliers, the platform remains responsible for the quality. Hence, the assessment of the supplier's capabilities, the rating of the suppliers and the possibility of excluding non-performing suppliers are the tools to be used and continuously improved to address quality problems.
- Invest at the *platform level* in quality inspection devices and competencies; this means that each part (or sample of parts), before being delivered to the customer, has to be physically moved to a central inspection facility where quality is evaluated. Although cumbersome, some platforms are following this way.
- Guarantee the state of the machine and the process that performs the operations on the part but do not give a direct guarantee on the obtained result. Therefore, platforms could *certify that the process* has been done on machines with given characteristics that are permanently maintained and kept under control, then is up to the user to understand whether this is a sufficient guarantee for quality.

The last approach is an opportunity to simplify the quality problem and is already appearing in some customer-supplier relationships when the capability of the processes involved is high. In this case, companies are already pointing out that defining tolerances on drawings, and measuring those tolerances on parts both after production and in incoming inspection, represent a very high cost in comparison to the risk of having an out-of-tolerance part. Therefore, in these cases sometimes the tolerances are eliminated, and the control is on the characteristics of the machines. For instance, in metal cutting this may become a very significant trend since, on the one hand, tolerances on the parts are pretty stable in many sectors (for instance values of dimensional tolerances of a couple of hundredths of a millimeter are quite common in automotive and many other sectors) whereas machine precision and repeatability are continuously improving with the top commercial machines to be used in a normal shop floor already going in the order of five to ten microns. Given this evolution, soon the capability of the machines will be high enough to guarantee with very little worrying the automatic satisfaction of tolerances on most of the mechanical parts produced (provided that processing cycles are not involving extreme conditions). Therefore, one possible evolution is that manufacturing platforms use a production base with high-quality machines and tools which are continuously monitored and correctly maintained. This for instance may be more easily guaranteed if an EP providing top and perfectly maintained machines and an OP monitoring the machines are adopted by the suppliers of the MP. In turn, high-quality manufacturing base will be a winning commercial argument in the competition with more traditional approaches to manufacturing where the installed production capacity may be fairly old. Also, in this case, MP, EP and OP would be at the forefront of technological evolution and would gain experience with innovative machines thus acquiring a competitive advantage from a technical point of view.

6.1.5. Organization of production networks

Manufacturing platforms embody a special form of *production networks* where products and related services are provided by autonomous companies which are linked to the market by a platform operator [133]. As it was discussed before (see Section 5.3), due to the centralized role of the operator this structure is star-like and shallow, there are no lateral links between the producers. A specific feature of MPs is the apparent lack of central inventories. Decisions on manufacturing and logistics are decoupled since in MPs the flow of material is typically the responsibility of 3rd party logistics service providers. These operate via all possible transportation modalities. The relationships are relatively stable, and the flows of information and financial assets are well controlled by advanced ICT and contracts, respectively.

This setup offers some definite opportunities: first and foremost, increased *flexibility*. Producers involved in an MP can cover a broad range of production capabilities and capacities, so even without the advanced CPPS techniques, notoriously expensive flexible resources at the nodes, as well as explicit inventories, the network can assume high flexibility, in every aspect of the term. Secondly, since producers can dynamically offer only a portion of their underutilized resources, an MP directly facilitates the *sharing* of manufacturing resources [229]. Third, the platform can dynamically *match* actual demand and supply, and on a longer horizon, with a good chance to do it better and better, following a *learning* curve. Fourth, the customers do not have to have lots of certified suppliers but may just request parts. Finally, platform-wide, centrally arranged logistics has much more room for optimized deliveries, where along with time and cost factors also environmental issues can be considered. All in all, MPs have the chance to operate with a higher responsiveness towards volatile market demand, better utilization of production and environmental resources, and with an improved OEE.

These opportunities can only be realized if the *footprint* of the network is carefully designed [133]. Indeed, since platforms are dynamically evolving and their structure is emerging, rather the rules of their formation should be well-defined. This needs planning and optimization considering main aspects like markets, production, logistics and their overall ecosystem which is just against the actual flat structure and distributed responsibilities of MPs. The key issues are whether we can identify appropriate platform footprints along with rules and incentives which drive the evolution of platforms towards the realization of these footprints.

Given the peculiarities of MPs, the *selection and qualification of producers* is clearly a key problem. Platforms normally have a qualification procedure to enroll a new producer. The baseline is that the producers must show the capabilities to produce typical parts required by the market. The potential new producer is required to produce test parts which are then accurately inspected by the platform and if specifications are met the potential producer passes the test. Other information like the type and number of machines, software adopted, the internal organization, as well as information on the company, are also analyzed to finally accept the producer. Some platforms go one step forward and instead of simply asking for certain capabilities, they try to integrate both their customers and producers into the network in a much deeper way. In this case the strategy is not to enroll many but rather some precisely selected producers that can guarantee superior performance in a niche market. This strategy is akin to co-platforming of products and manufacturing systems [51,132].

Matching incoming dynamic demand with available supply is the next main task to accomplish in an MP. Again, from the very nature of the platform, it follows that this matching is immediate. There is no strategic collection of demands in a wider time window which would give room for optimized planning. The simplest matching algorithms can assign demand to producers having sufficient technological capabilities using some ranking scheme. In any case, producers have a short time frame to respond. In case of a negative (or no) answer, iteratively the next producer can be selected. More refined matching schemes can employ *auction mechanisms* and *bidding* where delivery time and price matter. Quality is non-negotiable. Even more sophisticated matching algorithms can also be applied with some guaranteed properties. E.g., in the domain of additive manufacturing, a stable matching algorithm is presented for the allocation of production resources to customers [277].

The next issue is *coordinating the supply channels* between the platform operator and the producers. Under the actual circumstances, this is relatively easy because due to the specific mode of operation of MPs single-product channels are maintained, no forecasts on expected market demand are communicated, nor are inventories involved. Extending the operation of platforms in these directions is a topic of future research (Sections 7.1 and 7.2).

Platforms should though put much emphasis on the *performance evaluation* of the producers. A non-performing producer can spoil not only a particular business with a customer but also the overall reputation of the platform which may have a detrimental impact on many companies working for that given MP. Hence, platform operators run pragmatic *ranking schemes* of producers, based on delivery performance, quality, price, and customer feedback. These indicators are internal and are kept typically as private information between the platform operator and a producer. They express a measure of *trust* in the producer and are directly used for matching when customer orders are assigned. So far, it is rather suggested by common sense [257] (and at times, by specific simulation studies [228]) that including trust and reputation in the management of production networks can make their overall operation more efficient in the long run. Elaborating a fair and operational system for maintaining evidence-based trust in an MP is a challenge for future research.

Finally, MPs can also optionally support *procurement*, the supply of materials to their producers. To warrant quality—one of their most precious assets—MPs may employ standard incoming material quality inspection protocols. Inspection can be done by the single producer which has to guarantee not only conformance to design specifications but also the material quality. Alternatively, the quality of materials can be analyzed centrally but the critical issue in this case is that platforms operating for many clients need to process a wide variety of materials which in turn may require various quality control methods and expertise. Should the MP have all the instruments and capabilities to evaluate the quality of all the possible incoming materials? This would represent a difficult and expensive task, therefore most probably this is not the way MPs can go in order to be competitive. One way to simplify the problem is therefore again to modify the customer-producer relationships.

Hence, manufacturing platforms may decide to specialize in some materials and be able to provide products only in those materials. For those materials they may become specialists and guarantee inspection and quality for all the producers in the platform. They may even acquire these materials in a centralized way and have significant commercial power which means lowering input costs and having supplies guaranteed in critical periods. This way of operating clearly means that a platform will not be able to provide all the possible materials a client may require. However, if the portfolio of materials is wisely selected clients may find reasonable materials for their purposes. Therefore, the customer-producer relationship goes the other way around: it is the producer that imposes the portfolio of materials on the customer and not vice versa. This may sound strange in areas like forming or metal cutting but is quite common in additive manufacturing. It shows that limitations can be imposed on the customers that will introduce these limitations as constraints in their design processes. The portfolio of materials will become an important element in the competition among platforms.

6.1.6. Production management, planning and scheduling

While production planning's main concern is how to attain business goals in the future, manufacturing platforms operate practically in the present. Hence, the typical problems of production planning are not yet really relevant when managing MPs. Well, one could take platforms as multi-factory production networks [149], and then all the key issues would emerge which have to be resolved when managing the operation of (global) production networks [133]. The first essential point is *forecasting* market demand on a longer horizon. Since the platform operator handles all incoming orders, by responding to the demand of thousands of customers it can amass such a big amount of data which may already be sufficient input for up-to-date machine learning techniques. However, all predictions of demand are burdened by inevitable uncertainties which are mostly compensated in normal production networks by *inventories* and inventory policies. However, in PBM just this element of production management is missing. Of course, individual producers may keep inventories, but it is their internal business. The platform as a whole does not maintain and take responsibility for such buffers which would warrant the smooth flow of material even in case of deviations from the expectations. As we have seen in our case studies, that would be against the very essence of PBM.

Manufacturing platforms can rather exploit techniques of production management which were developed for handling demand for a broad variety of products on a short, immediate horizon, where products are needed in low—often one-piece— quantities. Such kind of operation where the numbers of orders are high, quantities are low while the variability of products is increasing is not unknown to manufacturers: it is termed as *high-mix low-volume* (HMLV) production. Fig. 18 shows a typical example of the demand distribution an HMLV manufacturer should routinely satisfy: columns of this heatmap give for each product family the weekly demand, and the rows define the weeks over an annual period. Values are relative and color-coded: average order volumes are marked in blue color, and deviations are shown in colors starting from green up to red.

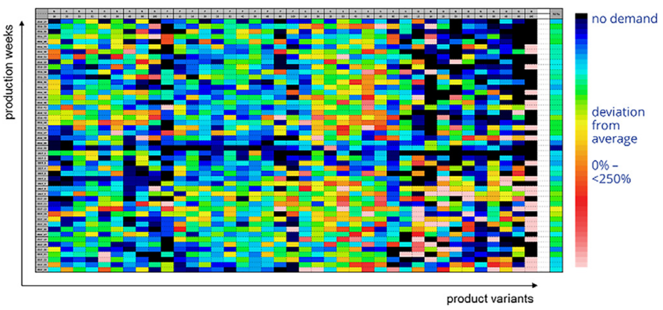


Fig. 18. Typical HMLV demand mix: weekly demand aggregates of product variants over a year (adapted from [77]).

HMLV manufacturers developed methods that helped them adapt to this specific situation and remain competitive by responding to the fluctuating demand in a flexible way [14]. Some methods which rely on extensive modeling and simulation, let alone running a digital twin of the company are clearly inapplicable in PBM, but there are some other opportunities, too:

- The platform operator can decouple volatile demand from production by *aggregating demand and leveling orders* so as to balance the mix and volume assigned to the producers [14]. Production leveling can particularly be applied when the assignment of production orders is the sole responsibility of the platform operator who knows the actual free capacities of the producers.
- *Lot-splitting* and *load-limiting* rules applied to order releases towards the producers can be effective whenever requested delivery times are short. Workload control methods improving the performance of HMLV production can certainly be applied also in PBM [237].
- *Grouping of products* by ABC/XYZ analysis into families and defining patterns for instant quoting, process planning, producer selection and quality control can improve the quality and timeliness of decisions and thus stabilize the service level of the platform [13]. Since the platform operator collects centrally the incoming orders and receives also direct feedback from the customers, this kind of analysis is a potential target of machine learning methods (see Section 7.1).
- The platform operator can develop an *evaluation scheme for its producers* including also organizational and technological aspects. Such a measure focusing on machining equipment effectiveness can contribute to increasing machine equipment effectiveness and throughput, as shown specifically in an HMLV production environment [7].

6.2. Challenges for organisational and business models

6.2.1. Service-oriented business models

It has been broadly accepted that *service* became a dominant logic in the economy which can give a new perspective for understanding and interpreting economic phenomena behind production activities, too [244,260]. According to this view, value is created collaboratively, during a mutual exchange of intangible ideas and tangible goods between customers and producers. Service implies the use of specific resources and competencies of one partner to the benefit of another, rather than the “simple” delivery of some products. However, with engineering services in the domain of manufacturing, one has to cope with requirements so far mostly unknown or irrelevant to manufacturers: namely, that customers and their operations interact with the equipment suppliers. This interaction can be the source of variabilities for demand, availability, and preferences, all being essential factors in service. When finding PBM’s position in the service-oriented world, ideas related to organizing service supply chains may work well [66,154,272].

Behind any kind of service, there must be a *cooperative* attitude, since its essential question is “What can I help you?” When looking for an answer, autonomous stakeholders have to align necessarily their disparate interests. For instance, remaining in the context of PBM, even traditional supply chain coordination problems can be taken as a service. In this setting, upon receiving some forecast of expected demand, the supplier warrants the delivery of products even in cases when the realization of the demand deviates from the prediction. Hence, it provides not only products with guaranteed service levels but also flexibility to its customer. Of course, pricing this service should depend not only on the products produced and delivered but also on the reliability of forecasted demand which is communicated by the customer. Under well-defined conditions which provide an incentive to give as reliable demand forecasts as possible, such a service can warrant minimal total costs (which may include environmental cost factors as well) along the channel [49]. However, any supply-as-a-service models need forecasting, planning and some sort of inventory accumulation and handling if the service of material goods is expected imminently.

Nowadays, providers of dematerialized services (like streaming, and gaming) use unanimously some sort of *recommender systems.* These fully digitalized systems can have access to an excessive and continuously growing body of information both on the side of demand and supply, hence providing an ideal ground for big data analytics and machine learning. In PBM, returning customers may receive special offers, and the matching between customer demands and producers can also be improved this way. Indeed, the development of recommender systems became a specific, distinct branch of AI research [118]. The performance of such systems can improve over time. Applying these AI technologies is still an untapped potential for PBM and could provide a competitive advantage to the first adopters.

6.2.2. Implications for the capital goods market

PBM is not only going to affect the competitive market of part manufacturing but will also have a deep impact on the *market of capital goods*. Indeed, on the one hand, manufacturing platforms may in principle support their suppliers in the sourcing of capital equipment. Therefore, manufacturing platforms, once grown in terms of volumes, may represent an increasing portion of the request for manufacturing capacity. This new competition model may be extremely disruptive since many machine tool builders are small or medium enterprises (SMEs) and may suffer if the market instead of being characterized by many clients with rare acquisitions transforms into a market of few big clients with frequent orders.

On the other hand, machine tool builders may change their business towards equipment platforms which entail a new business model where machines are not sold but they are paid for the use of the functions they provide. In this case, a machine tool builder sells functions which can be hardware (i.e., directly related to the transformation of material) or software (e.g., maintenance, process planning, production planning). Availability of the machines, quality of the products and even service level toward the final customer become more and more responsibility of the machine tool builders that acquire much more strategical information on the use of their machines.

In this new scenario, it is evident that the monitoring of components of lines and machines will become more important, for availability and OEE will become the major issues. Data exchange, access and usage control as well as payment streams and their monitoring will become more important than in transactional sales of machines. As it has been shown in the use case section, some machine builders have already started to launch types of machines that are directly targeted for these types of business models. In particular, the challenges for the machine tool builder are:

- Increase the *reliability* of the machine tools since the responsibility for availability shifts to the machine tool builder.
- Extend *sensing and data acquisition* from the machine since machine tool builders, as owners of the machines, have more rights to acquire data from the field and at the same time are more interested in the early detection of potential problems and in guaranteeing the correct and fair use of their machines.
- Increase the *flexibility* of the machines to make them adapt to many different uses. In some cases, some features of the machines may be blocked at the software level when not required by a particular client.
- Improve the *modularity* of the machines so that it is possible to reconfigure the machines and give them to new clients when the pay-per-use contract expires.

As can be seen, the changes needed to embrace the equipment platforms idea entail the challenge of a profound rethinking of the machine design from the side of the machine tool builder. These changes cannot be done in a short time and in most cases require a complete modification of the design culture of the company. Therefore, even if the most visible effect is the change in the business model, the most critical challenges to be successful reside in the technological areas of the company.

Regarding the business model, the more significant changes are in the revenue model. Since machines are not bought the financial burden stays on the machine tool builder which either must have an extremely strong financial position or must take the opportunity to engage in a collaboration with a financial partner. Another opportunity, since a machine tool is normally made of components (e.g., spindle, axes, NC) that are assembled by the machine tool builder, is to extend the pay-per-use model at least to the first-tier supplier.

Indeed, if the machine is provided pay-per-use in principle, also the main components of the machine could be acquired on a pay-per-use basis. As a result, the financial burden is diluted along the supply chain of the machine tool builder. This in turn entails technological changes in the design of the components for the same reasons described above for the whole machine tool. One important opportunity is that in this scenario component manufacturers are able to monitor their components in use which represents a major change in the data and information ownership and use.

6.3. Challenges for information and communication technologies

6.3.1. Asset and process modeling, semantic interoperability

As already mentioned, the CIM era in the 1990s brought various methods of business process modeling (BPM) and asset modeling, e.g., for the means of material flow simulation [192]. Some BPM methods as the Integrated Enterprise Modelling (IEM) modelled assets like machines and other manufacturing equipment as objects of the class “resources” with a special set of attributes [169]. Today it is still possible to use these types of models to derive PLC code and thus make the commissioning of manufacturing processes much easier and faster [101]. Asset modeling is relevant in the following cases:

- *Commissioning* of machines and lines, whenever a kind of machine-readable self-description can be used to parametrize the lines faster or link the machines to superordinate ICT systems [210].
- *Propagating changes* on the equipment to all interested and relevant partners of the machines, lines or plants. In this case, all relevant entities during the development of plants, machines, and components shall be able to properly react to adaptation requests.

Up to the definition of the Industry 4.0 asset administration shell, these adaptations used to be executed manually and were thereby error-prone and time-consuming. Following the ideas of Industry 4.0, any adaptation should be (semi-)automatic and self-controlled by the entity or the production system. This capability, defined as *plug-and-work*, has been envisioned for a long time [152]. It is the ability of a production system to automatically identify a new or modified component and to integrate it correctly into the running production process without manual efforts and changes within the design or implementation of the remaining production system. All entities involved in a plug-and-work scenario must have the same processing and understanding of the relevant information, thus, they have to be interoperable. Interoperability of entities in general is defined as the degree of their integration as measured by the interaction required to fulfill a common goal. Here integration is seen as the process of establishing a system out of interacting system elements.

One possibility for a neutral, open, free and XML-based data exchange format for process and plant description is AutomationML^{TM}, being developed by the AutomationML consortium since 2006. It is a candidate for modeling products, processes, and resources as required in plug-and-work scenarios. It is especially intended for use within the production system engineering domain and is internationally standardised within the IEC 62,714 standard series. In the context of plug-and-work, AutomationML describes the contents, i.e., what is exchanged between the parties and engineering systems involved. It serves to model plants and plant components with their skills, topology, interfaces and relations to each other, geometry, kinematics and even logic and behavior. In 2014 AutomationML [151] was combined with OPC UA [158], which made an online version of the model possible; AutomationML models could then be exchanged via OPC UA and include OPC UA data management, online communication functionality, multiuser support, access methods, security, etc. This is especially important for re-engineering and maintenance use cases where the AutomationML model evolves over time [93]. This work was a step towards the modeling of the Asset Administration Shell (AAS), which is now a standard for semantic interoperability in Industry 4.0 applications and thus delivers partial models of digital twins [161,231,246,264]. Meanwhile, there are reference implementations of the AAS available, so that users from research and industry can model their own AAS network [3,223]. The AAS is one of the basic concepts for sovereign data exchange within data spaces (see Section 6.3.3).

6.3.2. Transparency and traceability

Transparency and traceability represent further important challenges for PBM. Indeed, since the connection between the user and the producer is not explicit how can *traceability* be guaranteed? The answer is that in general there is no traceability unless it is explicitly required. In a sense, traceability creates an issue at the heart of the business model of the platforms which is based on the disintermediation of the relationship between the user and the producer. However, since traceability in some cases can be a compelling requirement, platforms have to give some answers to this problem, like the *digital product passports* (DPD) providing environment-related information about the product. The first answer is to guarantee traceability through the platform. The idea is that in case it is needed the platform can collect all the available data to identify the producer of each part and even the machine and the parameters used in machining the part. Hence, the client may receive a unique identifier of the part and when needed it is possible to access all the data by means of this identifier. Therefore, traceability is possible but not explicit or, as already said, it can be guaranteed through the platform. A second option is to break the anonymity of the producer. This can be done in special cases, normally with big customers and with guarantees at the contractual level. In this case the platform behaves more as a *procurement* department for the company without the risk that the company may use the traceability information to circumvent the relation with the platform for future orders. A first example for the DPD is the digital nameplate proposed by the German ZVEI [284].

Transparency in multitier supply chains is hard to achieve because most of the involved enterprises are reluctant to provide cross-company transparency of data or tracking services [173]. The challenge is even higher in platform-based ecosystems (see Fig. 19) where the problems indicated in the previous paragraph appear at more levels. The approaches described above can be applied also in such settings but in a more complicated way. The solutions to keep data sovereignty and security (Section 6.3.3) can play an important role here.

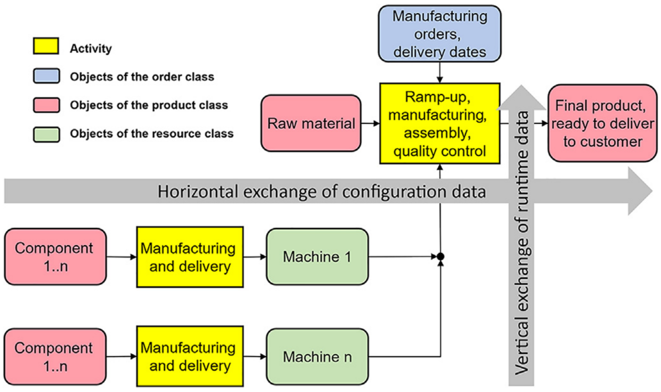


Fig. 19. Distinction between configuration and runtime data.

6.3.3. Data sovereignty, multilateral data exchange and data spaces

In times of increasing digitalization, data represent an important resource worth protecting. For this reason, the European Data Strategy [56] has been evolved with the aim of offering a single marketplace for data in the European area that is subject to European legal and security guidelines. One major milestone for companies to protect themselves and their IT-infrastructure is IEC62443, an internationally recognized standard that aims to address and secure industrial automation and control systems (IACS). For this purpose, the standard contains procedures and requirements for the target groups of factory operators, service providers, system suppliers or integrators and product suppliers. It is necessary to consider cyber security from the very beginning (security-by-design) when developing new components, systems, and plants. At the same time, it is important to guarantee the highest level of data sovereignty for the data producers and consumers. The following goals are being pursued by the current European Data Strategy:

- Data should be able to be transferred within the EU and across industries.
- European values and rights are to be fully upheld.
- The rules for the use of data should be fair, practicable, and unambiguous.

To this end, dataspaces should enable access to privacy-compliant use of data by creating suitable data-related ecosystems. An ecosystem infrastructure should facilitate data integration from multiple data sources and should support data federation, data analytics, and machine learning in compliance with data protection requirements. Partners who feed in data should be given access to larger volumes of data, and if necessary, should be able to profit from the analysis results of others. This idea enables new business models based on data.

As one of the latest results, the Plattform Industrie 4.0 has defined how companies can make use of data spaces: “From the user’s perspective, a data space provides a trusted environment for multilateral collaboration between companies, e.g., from the integration of data sources, through storage and data access management, to data analysis and value-added services based on data analysis [. . .]” (see [61] p.19). Although a data space is made for multilateral data exchange, it is not a free zone for the unlimited access and use of data. Standards for usage control and protection of intellectual property or payments are crucial.

For companies operating autonomously in a market environment, it is essential whether and what data from their customers, supplier, products, production technologies, production lines and factories are passed to third parties. The usage control of data must remain with the data owner. For this reason, *reference architectures* should support the aspirations of the IDSA, which is establishing the Industrial Data Space (IDS) as a secure and sovereign network for data exchange. Using IDS features, the data is protected through usage policies and their tracking, so further usage by third parties can be traced. For instance, it is not only possible to restrict the persons receiving the data but also the way how the data is processed. Researchers have already developed the first connectors, e.g., for OPC UA, including major IDS features. The partners of the Catena-X project have developed an Eclipse Dataspace Connector (EDC) based on the IDSA principles to facilitate data exchange in a value-adding chain in the automotive and supplier industry. There are different types of sensitive data (see Fig. 19):

1. *Configuration data*, ranging from the customer order and the parts’ geometry to the feature descriptions of the assets and their life cycle data including data exchange with suppliers and their sub-suppliers in the machine builders’ value network.
2. *Runtime data* that is collected during the operation of machines and their components.

All this data represents part models which may be captured in digital twins. Of course, these part models are also exchanged between numerous organizations − which means that data sovereignty, distributed data management and distributed learning should form the basic principles of a trustworthy data economy according to GAIA-X principles (see Section 4.3). In PBM, warranting the *security* of data is a special concern. Here, the results of generic studies can readily be applied. For instance, the taxonomy of attacks’ goals, methods and targets related to digital manufacturing (see also Fig. 20) can also be used for platform-based manufacturing [157]. Furthermore, to protect the security and privacy of PBM, innovative technologies, cryptographic solutions, intrusion identification, and blockchain technology are broadly available.

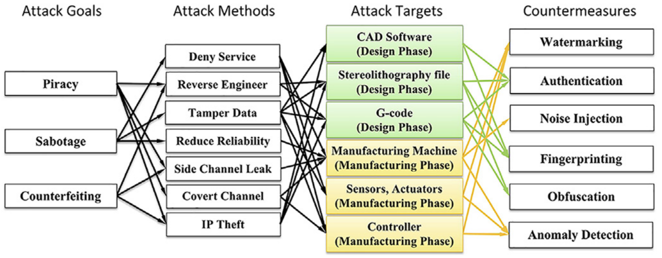


Fig. 20. Threat taxonomy and corresponding security measures [157].

7. A vision of the future of PBM

In the previous section, a detailed analysis of the challenges and opportunities related to the various aspect of PBM has been discussed. While it is very important to analyze in detail the various technological issues that may support or hinder the growth of platforms, it is also important to look the advent of platform from a more strategical point of view which cannot be captured by the simple combination of the various elements. Some aspects of this analysis have already been provided in Section 3, where the issues related to the introduction of platforms into existing ecosystems has been presented. In this section, the strategical role of platforms looking towards the future is proposed. In particular, emphasis is given to the role of knowledge, to the decentralization and distribution of roles and functions, to the role of platforms in circular economy, to the issues of collaboration vs. competition. These elements are far reaching and go in the direction of relating platforms to the context of society, economy, norms and laws.

7.1. *Learning from concentrated experience, knowledge sharing*

The success of platform companies is greatly attributed to their digitalized and scalable operational model which enabled them to continuously gather, store, integrate and analyze data at an extremely large and ever-growing scale. *Learning* from data sources, making a new offering to customers or more efficient operational decisions as well as taking advantage of network effects became an ingrained mode of operation of these data-crunching companies. Feedback to the data-driven changes and innovations arrives almost imminently, thereby constructing an ideal, self-reinforcing machine learning loop [109]. Indeed, collecting data on a big scale, AI-based data analytics, as well as network effects can go hand in hand when creating new value positions and customer relations. This in turn opens new opportunities along with generating even more data as well. However, by using more data one can offer better customer services and greater incentives for third parties to join the network. As was shown for the travel industry, these coupled loops greatly increase the potential for learning and reinforce network effects. All in all, the larger the network, the more data it generates, the better the analytics and decisions, and in the end the higher the value the network can deliver [105]. Given sufficient computational resources, this data-centric mode of operation can be extended in terms of scope, scale, and learning, without actually encountering traditional operational constraints.

Massive data processing and storage techniques characteristic of the cyber-physical production systems can provide ample input sources to big data analytics also in PBM. Machine learning is becoming a more and more important tool, with the promise of more agile, lean, and cost-efficient manufacturing. The usefulness and necessity of data management and data analytics are properly described in some recent industry insights and reviews [35,68], which also shared very practical application hints.

In PBM, platforms provide mechanisms for harnessing and utilizing the collective intelligence of various parties participating in product realization. There are four main aspects of learning:

- *Product and technology*: As more and more product-related information is handled by a platform, so grow the chances of learning. By relying on similarity-based learning techniques, a platform can make better interpretations of the design intent and give more precise instant quotes. An MP can even acquire process planning knowledge [83] and instruct the manufacturers which programs to use for producing the parts. The unique manufacturing expertise is thus transmitted to the platform without anybody taking notice.
- *Market demand*: When demands for many products (and product families) are collected in one hand, at the platform, then better forecasts can be made for future demand. Aggregating demands can be used to predict what the overall network of producers around the platform might do.
- *Equipment*: EPs collect data about running machinery continuously, which is a valuable source for predictive maintenance, and even for improving machine design. Here edge IIoT techniques with embedded AI can be most useful.
- *Provider*: Repeated encounters with providers make it possible to build and maintain a model of trust/reputation with them. The ranking schemes applied in every platform are the first, evident steps towards this direction.

In any of the above forms of PBM, learning opens new possibilities for accumulating knowledge which could not otherwise be acquired. But who owns this knowledge, and who monetizes it? How can the benefits (and risks) be shared? Does this knowledge come with extra power and consequently, a new share of control over the market?

Further dilemmas are that analytic methods which can work over very large datasets have rather limited capabilities to exploit the available engineering background knowledge. Big data tends to be far more focused on correlation and misses causation [185]. In the domain of PBM, this is still a serious weakness of contemporary techniques of machine learning. The emerging AI technology of *knowledge graphs* whose variants are unanimously used by global platform companies [31] may provide the key to resolving this dilemma on the long term.

7.2. Decentralized production management, inventory policies

Apparently, most manufacturing platforms discussed so far supports the delivery of products manufactured by a single supplier. More complex operations like assembly or the composition of products from parts delivered by different first and n-tier suppliers make the organization and management of platforms more complicated, even if the supplier “hides” its overall supply network. However, in the successful operation of platforms time and reliability are of the essence. In any case, when the expected lead time may exceed the delivery time acceptable by the customer, and/or supply could be burdened by disturbances, buffers – i.e., inventories – are to be created to decouple marked demand from production. Alternatives of this decoupling are known also as variants of make-to-stock (MTS) and make-to-order (MTO) production.

Distribution platforms adopt some form of the MTS production strategy and define their inventory policy which fits best the market demand, lead time and cost structure of their particular products or families, as well as the operation of the logistics service provider. For them, theory and practice of inventory management offer a host of applicable policies and methods [73]. Since suppliers are not directly connected to the market but, at the same time, are obliged to provide high-performance services, a Vendor Managed Inventory (VMI) model which supports the communication of medium-term demand forecasts along with short-term delivery requests and schedules can be a solution. Even their business model can be tailored to this asymmetric information situation by making the platform responsible for the quality of the communicated demand forecasts [49].

In case of some disturbances, the platform can involve additional producers, as an alternative to the larger inventory. In any case, benefits of decoupling, such as higher productivity, mitigation of risks and uncertainties, as well as reduced stress can be exploited only if some scheme is found that facilitates the “laughing and crying together” of all partners involved in PBM.

7.3. Towards circular economy

Circular economy is becoming a reality, especially in advanced countries and examples of companies embracing circularity are growing [112]. Surprisingly at the moment, circular concepts are out of the radar of manufacturing platforms. Platforms are at present completely concentrated on growing their manufacturing business which, as it has been shown, has huge potential but also problems to be solved. Therefore, currently platforms cannot dedicate effort and resources to *de-manufacturing* and *re-manufacturing* concepts and activities [239] which are central to circular economy and are extremely important in shaping the future of manufacturing. Current platforms see these activities as potentially interesting but only for the future with no real actions taken at present. This area is an open field for research and development and at present, it is only possible to elaborate some visions for the potential of manufacturing platforms in this field. However, platforms could realize each of the five strategies for closing the material circulation loop as identified in [112].

With respect to *recirculating materials*, platforms may play a central role if, as mentioned in Section 6.1.5, they operate only on a portfolio of materials. They could easily enter the business of collecting parts of those materials from the customer they served and organize their material regaining activities. In comparison with their clients indeed they may collect much bigger quantities of the same material to be regenerated and the incoming flow may be more stable since platforms receive end-of-life parts from many different suppliers operating in different sectors, therefore, the variance in the supplies of end-of-life parts may be small.

As for *recirculating parts and products*, some platforms have already an internal channel to reuse regenerated material. Hence, platforms could not only provide parts but could also provide the service of taking back the parts at the end of life offering advantageous economic conditions. This service would be very important if, as already mentioned, MPs do not only produce “one-of-a-kind” parts but start producing bigger volumes. This service could become vital for the platform business if regulation in the future will enforce the regeneration of products. Concerning the regaining of whole products or product functions the scenarios are harder to delineate since MPs at the moment tend to provide only parts and not components or whole products.

Therefore, the current limitations outlined in Section 5.3, namely the limited capabilities of platforms in providing assembled products will be reflected also in the difficulty of entering the business of product regeneration. Hence, the regaining of product functions will probably stay with the final producer (or with the product platform) which is the one that designs the product and its functionalities, interacts with the final customer and can orchestrate the business of product regeneration and upgrade. In this scenario, MPs may play a role if they offer services of part regeneration (i.e., inspection, testing, refurbishment and repair) which could serve as one of the steps in the wider business of product regeneration. In this area therefore it may be possible to see a future interaction between product platforms which could take care of the product life cycle and manufacturing platforms supporting some part (or maybe component) regeneration.

A completely different scenario is the appearance of new *de-manufacturing platforms*. In this case, by applying the *reduce and avoid strategy*, the platform may offer the service of taking care of the end of life of the products. This would be particularly valuable if government enforce (as it is already happening in various sectors) regulations for the end of life of products with responsibilities for the producer. In this case producers may want to have a one-stop shop to bring their end-of-life products which gives guarantee of dismantling in conformance to the regulations. This is already happening for instance with waste electrical and electronic equipment (WEEE) products [268]. These new de-manufacturing platforms can orchestrate the capabilities of many different companies dealing with different aspects of products, parts and material dismantling and regeneration. Therefore, de-manufacturing platforms may receive a product design and provide a quotation for its de-manufacturing. This quotation may include the offer of some regenerated parts (which can then be used by the company in re-manufacturing activities) and an economic reward to the companies since they provide the cores. Since de-manufacturing activities tend to be very diverse the complexity can be managed by de-manufacturing platforms by concentrating on a limited spectrum of product types.

The appearance of de-manufacturing platforms is deeply related to the regulations on scrap since the platform will deal with end-of-life products and material which, if simply classified as scrap, cannot be moved and exchanged easily among the companies. On the other hand, given the difficulties in regulations de-manufacturing platforms may be the first ones to be able to put together all the habilitations needed to complete the required operations thus making their offer to companies particularly valuable. De-manufacturing platforms can be part of new ecosystems where they may co-exist with de/re-manufacturing supply chains which may be able to regenerate and upgrade the complete product after use. Therefore, there may be a parallelism between the evolution of the competitive market described in Section 3 for the manufacturing of products and that for the de/re-manufacturing of products. These could be fine instances of applying the *rethink and reconfigure strategy*.

Very different considerations can be applied to *equipment platforms* since the circular economy can be at the core of their business model, especially if they adopt the strategy of *reinvention*. Indeed, having a platform that deals with a production capacity which is not owned by the user seems to be the ideal situation to promote the reuse of functions in the capital equipment products. The platform may give the capacity to a certain user but when the capacity is not needed anymore the same machines can be moved to another user. Hence, the continuous reuse of the functions of the equipment allows a truly circular approach to capacity utilization guaranteeing better saturation and longer use. Evidently, this results also in a change of the features of the capital equipment since more modular, flexible and upgradable equipment should be preferred as this can guarantee greater opportunities for circular reuse. Also, since maintenance normally becomes a responsibility of EPs, the tendency will be to use more reliable machines with longer life and more sophisticated remote supervision. Therefore, the EP will require from the equipment manufacturers specific features for the machines which tend to extend the hours of usage of the capital equipment possibly by a periodic reconfiguration and by allowing a more continuous and intense use. This goes in the direction of more sustainable production capacity. Since EPs will become big buyers of machine tools (or they will be owned by machine tool builders) they will impose important changes in the design of the machine tools.

7.4. Systemic dilemmas in PBM

Various forms of PBM discussed above are the results of a relatively short but extremely intensive evolutionary process whose conditions were created by technological developments, novel opportunities for making business and most importantly, the ubiquitous digitalization of industry (see Section 4). In this process of formation, where platforms competed not only with each other but also with more traditional ways of making business in manufacturing, selection pressure was provided primarily and almost exclusively by market success. Theoretical studies, elaboration of regulations and incentives, and institutional design were all left behind these rapid developments (for an early exception, see [243]). Hence, no wonder that the present variants of PBM inherently face some sort of systemic dilemmas whose resolutions are open questions.

As it is commonly held, platform-based ecosystems can generate almost unlimited *innovation* with outside complementors or producers and various customers [70]. Accordingly, via the interaction channels of a platform consumers can get involved in the value-creation process from its very beginning, thereby participating in what is termed *value co-creation*. This view has been espoused for a long in the production engineering community, too, for situations when in a not completely known environment service providers and receivers with (partly) uncertain objectives interact with each other [244]. All these might work for innovation platforms, however, in the case of manufacturing platforms it can be just the other way around. In an MP, the platform operator separates consumers from producers, and there are no lateral links between the various producers either. Market demand is transmitted to the producers through standardized channels, and there is no chance for direct interaction, let alone negotiation, with the customers. Loss of direct contact can but lead to loss of innovation potential, on both sides. Indeed, MPs as they work today imply the risk that manufacturing loses its essence of being a creative faculty and becomes yet another commodity. However, since platforms will coexist and compete with more traditional supply chains, the described reduced innovation potential may induce them to find ways to guarantee better cooperation among actors or to resort to productions where innovation due to interaction is not a critical asset to guarantee success.

Manufacturing platforms can operate as extremely flexible manufacturing systems, giving access to a broad and open-ended variety of technologies as well as machine and human resources. This offer can include very specialized, *niche skills and technologies*, resembling the era of craft manufacturing. For instance, as was observed in particular in the Chinese clothing industry [25], producers with very specialized skills were ideal platform contributors to meet an intrinsically HMLV demand. However, this setup is also not without risks: producers can get locked into a platform and may completely lose control over the business processes. As the level of automation increases, so will they have to comply with more and more standards and fail in the end to be the providers of some special competencies. Hence, it is still unclear how such companies—typically, SMEs—will find their right place in platform-based manufacturing.

PBM poses, as a matter of fact, a threat to SMEs, especially in high-wage countries, as they increasingly depend on the relevant platform. They are no longer in direct contact with their customers and owing to maximum transparency, competition is reflected almost exclusively in the price. To date, this is mostly true for commodities, i.e., the production of standard parts. However, as it happens today, most producers are not exclusively supplying platforms but they keep their own historical clients and resort to platforms only to saturate their production capacity. It is therefore not clear at the moment which model will prevail for SMEs.

Platforms have basically network-like structures which would imply that as a whole they are *resilient* against unexpected disturbances. This is so when the impact hits the fringe of the network, i.e., the individual producers. However, the specific, central role of the platform operator makes the whole—basically star-like—structure vulnerable. By design, there is no part of the network which could take over the role of the operator. Also, as discussed before, platforms tend to avoid stocks since they cover demand fluctuations with the very huge potential capacity of their producers. However, in critical situations where there may be a worldwide surge of demand, the lack of stocks may reduce the resilience of manufacturing. Finally, platforms may also be related to a single country while having worldwide producers and users. Therefore, a dominant platform may give a few countries control over the production and supply of other countries which has strategic implications in case of crises. Also, off-shoring and re-shoring can in principle be controlled by platforms and the decision between the two may become much more fluid.

As it was discussed above (Section 7.1), PBM is an ideal terrain for *machine learning*, given the huge amount of continuously incoming data and the feedback of customers. In particular, a platform operator may become a center of knowledge, amalgamating first-hand information both of the market and its producers. It can even prioritize those chunks of knowledge (i.e., in design intent interpretation or process planning) which prove to be the most broadly applicable. However, it is unclear where the rights of the related intellectual properties lie. Among the many stakeholders (see Section 2.2) who and how are sharing the rights of the new knowledge generated by learning?

Being part of a platform-based ecosystem brings new issues for companies that they have to deal with. If a manufacturing company starts to develop and provide *software services* for its equipment, other software functionalities are required to run and support them. Why should each SME, who are experts in their field of designing and building manufacturing equipment, develop these software services redundantly? Are there any communities or ecosystems of companies that could develop such services only once and agree on rules to monetarize them? For some companies it can be worthwhile thinking about an *open-source* strategy instead of keeping these services proprietary (open source does not necessarily mean “free of charge”). Therefore, it is evident that cooperation is a key success factor in digital ecosystems. To date, most of the manufacturing companies and equipment suppliers are not habituated to this type of sharing economy.

Finally, even though the platforms of today are the result of competition, new types of *cooperation* can emerge in PBMs in the future. Cooperation between the same type of platforms can increase their market share, i.e., in the case of MPs, they can take orders which surpass their individual capacities, moreover, they can cover a larger portfolio of processes or even some consecutive levels of supply chains. Cooperation between platforms of different kinds can also bring fruitful benefits. Natural cooperations can emerge between all three types of platforms offering services of higher level. The partners within the same platform can learn from each other or mitigate the effect of some disturbances. *Trust* can be built between the customers and the platforms and can be strengthened if the orders from the same customers are directed to the same partner by the platform operator, which was responsible for the previous orders. In this way, the quality of the product or service can be kept within tight tolerances. Platform operators can select between their partners also taking sustainability–first of all environmental–issues into account. Platforms are in the position to calculate sustainability indexes, moreover, they can communicate them towards the outside world. However, even though recent developments of ICT services such as semantic interoperability, transparency and traceability, as well as data sovereignty, multilateral data exchange and data spaces (see Sect. 6.3) establish the technological basis for interacting and cooperating manufacturing platforms, for the time being one can see only some initial traits of such a cooperative attitude, and it is open what incentives would drive the evolution of platforms toward these directions.

8. Conclusions

Platforms are the result of a long evolutionary process that has happened over the years in many different disciplines (manufacturing science and technology, organizations and business models, ICT) which at a certain point reached the maturity to create a disruptive change that appeared quite quickly. Many technical issues need to be addressed to make the manufacturing platform model fully operational but practical relevant successful examples are already existing and the model could be replicated in many more cases. This opens interesting new areas of research and new problem statements in existing areas. In particular, the areas of automated process planning, knowledge formalisation and sharing, distributed production planning, industrial automation, and cybersecurity will receive an impulse from the manufacturing platforms.

The introduction of manufacturing platforms is just at the beginning and numbers, albeit growing fast, are still extremely small in comparison with the total manufacturing sector. However, platforms have the potential to completely change the manufacturing world by introducing new actors that tend to become central in the market and control most of the activities performed. Platforms in particular introduce the concept that some of the functions currently performed by the companies can be extrapolated and managed by platforms. Companies, therefore, concentrate more on their core business but on the other hand become deeply dependent on platforms. Manufacturing platforms currently tend to concentrate on their business and act in a competitive way however cooperation among platforms may become essential to cover more technologies, more geographical areas and offer a wider range of services. Platforms also introduce the concept that supply chains can be broken as platforms become the orchestrator of the flow of material and information thus disintermediating the relations among companies. Platforms may easily become very big operators with very strong contractual power toward traditional companies therefore potentially reducing their margins and autonomy. The other side of the coin is that platforms may make the markets much more efficient, reduce overall costs, induce best practices, and favor standardization.

Manufacturing platforms have the potential in the long run not only to affect the actors in the manufacturing business but to affect the overall economy. Governments should have a clear strategy for manufacturing platforms since if doing so, the whole production capacity of a country may be positively affected. On the one hand, platforms may foster the technical growth of many companies introducing a new culture, improving efficiency and creating opportunities by diminishing the entry barriers for new companies. On the other hand, given the potential central role platforms may take, they could in practice control growing portions of the manufacturing base, especially, in countries where SMEs have currently a major role. Since platforms may operate transnationally, a platform may decide to allocate work to companies on a technical basis but in principle can use also other drivers. In addition, manufacturing knowledge may easily cross borders through platforms. Manufacturing platforms may become big buyers of machines which may have an important strategical impact on countries that produce capital goods.

Therefore, governments should not only monitor but also strategically drive the change of manufacturing towards platforms. Indeed, they can introduce regulations to guarantee competition among platforms, foster the creation of platforms, generate multilateral environments, impose interoperability standards on the exchange of data, impose regulation on the use of knowledge, and guarantee the freedom of the suppliers to serve multiple platforms to guarantee fair principles in the selection and use of suppliers. Since the problems are deeply interconnected, there is a need for the generation of new roadmaps focusing on the evolution of platforms that can help governments to analyze the phenomenon and take informed decisions.

The potential disruptive nature of platforms is the wonderful result of research which allows automation, interoperability, marketplaces, computational power, and AI and will certainly go one step forward toward more efficient, more resilient, more distributed, and faster evolving manufacturing. Any disruption creates winners and losers but should lead towards the overall benefit of our societies.

Declaration of Competing Interest

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

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