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the role of advanced manufacturing technologies
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Operating Digital Manufacturing in Industry 4.0: the role of advanced manufacturing technologies


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Abstract

This study analyzes the application domain of Digital Manufacturing while considering the new industrial paradigm. Based on content analysis, joint applications of digital manufacturing tools and advanced manufacturing technologies are framed and technological trends identified. The results reveal a new comprehensive framework that defines the application domain of digital manufacturing in Industry 4.0, as well as how digital manufacturing operates within Industry 4.0. The presented framework covers manufacturing life cycle phases, digital manufacturing tools used in each phase, and Industry 4.0 technologies used with the respective tools. The study contributes by positioning digital manufacturing conceptually and delimiting its application domain.

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1. Introduction

The digital revolution in manufacturing has moved from single technologies to integrated systems. Industry 4.0 describes the fourth industrial revolution, which leads to an intelligent, connected and decentralized production, standing for a new level of organization and regulation of a product’s entire value chain over its life cycle. Indeed, the advances in data storage and new computing capabilities, along with developments in technologies such as computational intelligence, automation and robotics, additive manufacturing, and human-machine interaction, are unleashing innovations that change the nature and content of manufacturing itself. Industry and academic leaders agree that digital manufacturing technologies will transform all aspects of the manufacturing systems of value chains [1,2].

Digital Manufacturing (DM) has evolved from Computer Integrated Manufacturing (CIM), which was developed in the 1980s when the reduced cost of computing meant computers could be used extensively for machine and automation control, planning and scheduling. CIM has worked as a connection between manufacturing, systematic science, and other related issues, and these merge into the manufacturing industry. From the combination of organizational sciences, such as Total Quality Management, Concurrent Engineering and Lean Manufacturing; with engineering science of CIM emerged the concept of digital manufacturing that highlighted the need for a more collaborative product and process design [3,4].

Although digital manufacturing converges to the central idea of manufacturing improvement using technology integration, there is a noticeable difference in this convergence and the application domain [5,6]. Second, it remains unclear
how Industry 4.0 technologies influence digital manufacturing, and whether these technological changes have changed their application domain or opened new possibilities for its use. Understanding how these new technologies interact with DM and how a new direction is created for the application is an essential step for organizations to effectively apply their resources and to promote greater value chain integration. Thus, this study explores Digital Manufacturing in the context of Industry 4.0. It does so by investigating the following research question: “RQ1: What is the application domain of digital manufacturing in Industry 4.0?”.

In addition, due to technological changes, the way digital manufacturing is used has changed dramatically over the last few years. Many of the advanced manufacturing technologies are not new, but recent forms of integration, improvements in use, and joint use have changed the digital manufacturing field as a whole, opening up several new challenges and opportunities. Thus, in order to understand the influence of Industry 4.0 on digital manufacturing, we also explore the following research question: “RQ2: How does digital manufacturing operate in Industry 4.0?”.

Through content analysis of scientific and technical papers, consulting reports and professional standards, various Digital Manufacturing roles are assessed assisting to define its current application domain.

2. Digital Manufacturing in Industry 4.0

Digital Manufacturing being under the umbrella of Industry 4.0 technologies and playing the role of integrating technologies and information throughout the product life cycle, industry leaders agree that digital manufacturing technologies will transform all aspects in the manufacturing systems of value chains [1]. A variety of concepts and solution-components were drawn and studied to fulfill the vision of Industry 4.0, and these technologies have a significant influence on current manufacturing. Most of these technologies that constitute Industry 4.0 are already used in manufacturing, but when integrated they transform production: isolated cells come together as a fully integrated, automated, and optimized production flow, leading to greater efficiencies and changing traditional production relationships among suppliers, producers, and customers—as well as between human and machine. Many models and frameworks are presented trying to structure this new industrial paradigm. Most of them are not only based on technological aspects, but cover structural and processual dimensions, competencies, capabilities, skills, and resource-based views [7–9].

However, the framework described by the Boston Consulting Group, as presented in Rüllmann et al. [9], developed an Industry 4.0 vision based on technologies. Seeking to understand the influence of Industry 4.0 technologies on digital manufacturing, we adopted this framework. The so-called ‘nine pillars of technological advancement’, encompass: Additive Manufacturing, Autonomous Robots, Big Data & Analytics, Cloud, Cybersecurity, Horizontal and Vertical System Integration, Internet of Things, Digital Simulation, and Augmented Reality. These technologies are directly or indirectly related to DM at different stages of the manufacturing life cycle, and impact it in terms of design, implementation, use or management.

To answer the research questions, content analysis is conducted to reveal the application domain and how digital manufacturing operates in this new context by the use of Industry 4.0 technologies.

3. Using DM with advanced manufacturing technologies

Next, we explore how the Industry 4.0 technologies influence design, implementation and the use of various DM tools. References are used from different fields to provide a comprehensive view, but with a weighting towards the use and application of technologies such as computer and systems science, computer engineering, and cognitive systems. Each subsection (3.1 to 3.8) is structured to present four main points: (i) an overview of each technology of Industry 4.0; (ii) how each technology is applied together with DM; (iii) how this joint application creates value; and, (iv) example(s) of such joint application and its respective phase in the manufacturing life cycle. Note that the technologies are listed in non-prioritized order.

3.1. DM and Simulation

According to Ribeiro da Silva et al. [10], digital simulation constitutes a core function in DM, since it supports experimentation and validation of different scenarios and configurations for existing and new manufacturing resources and systems, contributing to an improved design and performance assessment. Simulation involves modelling of processes or systems, so that the model mimics responses of the actual system to events that take place over time [11]. In a fully integrated DM world, a product, its manufacturing processes, as well as its usage and characteristics are all developed and simulated in the digital environment, before the first piece of material is even purchased. This saves considerable time and money in new product development, resulting in higher quality products and reduced costs.

The main difference lies in how simulation is used today, and at which manufacturing life cycle phase. The emergence of cloud technologies and real-time data acquisition allows simulations to migrate from a static and deterministic environment to a dynamic and stochastic environment. Manufacturing is facing the revival of ‘hardware in the loop’ control system design techniques. This is also connected with the concept of Digital Twins, first discussed by Grieves [12].

Real-time scenario analysis involving variables such as machines and equipment conditions, logistical and labour issues, enables simulations to improve targeting and resource selection for a given set of products and processes. This makes a significant difference by allowing an analysis of complex scenarios and creating dynamic decision-making mechanisms that are not possible in static environments, which could lack the integration requirements. For instance, dynamic simulations currently help to predict in real-time, how changes of a current process (process planning) that include insertion of a new product on the assembly line, influence the material flow on the shop floor (assembly analysis).
3.2. DM and Autonomous Robots

Autonomous robots are in a growing category of devices that can be programmed to perform tasks with little to no human intervention or interaction. An increase in autonomous robots being programmed with artificial intelligence to recognize and learn from their surroundings and make decisions independently are seen over the recent years. According to Fitzgerald [13], as autonomous robots become more sophisticated, setup times decrease, less supervision is required, and they are increasingly able to work side by side with their human counterparts. The benefits are expanding as autonomous robots become more capable of working independently around the clock with more consistent levels of quality and productivity, performing tasks that humans cannot, should not, or do not want to do.

The main role of autonomous robots in DM is to support the design and simulation of autonomous or hybrid workstations. For hybrid workstations, that integrates workers and cobots, DM tools allow robot programming (both on- and offline), manual task automation and simulation of worker-cobot interactions. There are industry safety standards such as ISO/TC 15066 dedicated to cobot installation that DM tools adhere to. Several use cases simulations are validated through the Virtual Commissioning environment.

Autonomous robots and cobots are typically used in the plant design and ramp-up for operations life cycle phases since they are an important technology for plant automation and commissioning. Two cases are presented by Rolland [14] using DM tools to simulate and optimize a production cell using cobots. In the first case, DM tools helped identify possible collisions between the cobot and the product being produced. In the second case, DM tools assisted to find the optimal position for the worker in terms of ergonomics and security in real-time simulations of collaborative tasks between humans and robots. Through DM tools, such as reachability analysis, it is possible to identify and eliminate hazards connected with autonomous robots.

3.3. DM and Cloud

The emergence of cloud computing represents a fundamental change in the way IT services are developed, deployed, scaled, updated, maintained and paid for. Cloud computing is a style of computing where scalable and elastic IT-related capabilities are provided as a service to external customers using Internet technologies [15,16]. The National Institute of Standards and Technology (NIST) define the following three service models related to cloud computing also known as the SPI model: Software as a Service – SaaS; Platform as a Service – PaaS; and Infrastructure as a Service – IaaS. IaaS provides users with computing and network resources such as high-performance servers, cloud storage, and wireless networks. PaaS provides a development environment or a platform that allow users to develop and manage cloud-based applications without building and maintaining the infrastructure. SaaS provides access to cloud-based DM tools such as CAD and FEA over the Internet [17,18]. Thus, manufacturing companies may cut costs, and free IT departments to focus on strategic projects rather than daily operations.

This type of service outsourcing has emerged as a possible solution to some of the problems encountered for proper use of DM. The use of DM requires a robust data infrastructure regarding data storage, transfer, and processing to mitigate the loss of productivity. Finally, high processing power is required for both analysis and simulations that demand a high capacity of hardware for execution. Providing sufficient infrastructure is a key obstacle to the effective use of DM, and the cloud is an appropriate technology solution.

The main role of cloud technology in DM is to enable data to be collected, processed, treated and accessed in an integrated and real-time manner. It has been used as the basis for several DM systems and life cycle stages covering, from product engineering and plant design, where it has a role of intra-departmental and intra-organizational integration, to ramp-up for operation and production management phases, where the cloud supports collection and makes data available in real-time for simulation, commissioning and operations management.

For instance, Siemens Intosite presents simple and intuitive access to up-to-date DM and production information from the shop floor [19]. The solution deploys the digital factory as a SaaS application, meaning Siemens PLM Software hosts the application and associated data on the cloud, and customers can access the application via web browsers. This way, customers do not need to invest in new hardware or handle application installation, maintenance and support.

3.4. DM and Internet of Things

Internet of Things (IoT) is a key element for making DM more valuable. According to Turbine [20], the proliferation of cheap and reliable sensors provide greater real-time visibility throughout a plant, organization and supply chain, while sophisticated analytics and data visualization programs help managers capture intelligence from Big Data storages.

The main role of IoT devices in DM is the dual provision of accurate information in real-time. The possibility of obtaining real-time data from machines, equipment and processes open new analytical possibilities and fast result dissemination, thus assisting the decision-making processes.

The interaction between processes and digital products with real-time resource data provide information regarding availability, quality and costs with greater accuracy. Scenarios that consider more variables and use updated information make the analysis more valuable. Also, the final analysis and production plans can be repeated whenever necessary and before the product actually goes into production lines. This, in fact, contributes to operational production risks mitigation.

IoT devices are typically used in the ramp-up to operations phase in the manufacturing life cycle and are essential for digital plant integration, automation and commissioning. For instance, two applications where IoT are used within DM tools: (i) to allow full process and material synchronization, since plant integration and real-time simulation increases operational excellence; (ii) for predictive maintenance, providing data for equipment analysis to ensure prediction accuracy.
3.5. DM and Big Data & Analytics

The manufacturing industry generates more data than any other sector [21]. The more complex a manufacturing operation is, the higher value is captured from big data and analytics. Operations managers use advanced analytics to explore historical process data, identify patterns and relationships among discrete process steps and inputs, and then optimize factors that have the greatest effect. Auschitzky et al. [22] pointed out that many manufacturing plants possess an abundance of real-time shop-floor data and the capability to conduct sophisticated statistical assessments. Instead of backwards-looking reporting on past events, data is being used to predict trends and anticipate needs. Moreover, vertical and horizontal value chain integration increases data accuracy. A single source of data across all applications can provide reliable and actionable real-time information and more seamless communication among supply chain partners as well as across product generations [23].

One key role of analytics in DM is to correlate data to verify the influence of certain variables (not necessarily pre-selected) in the production system. This helps scenario modelling by correlating otherwise unseen variables. It also provides conditions for analyzing existing patterns (such as process and resource failure), to improve predictions of simulation models.

Big Data and Analytics are typically employed to better use DM tools mainly in planning stages, ranging from line balancing to real-time production management. For instance, airplane manufacturer Boeing is integrating its entire value chain into a single platform, where the digital continuity can improve data and analytics capabilities and use DM tools more accurately [23].

3.6. DM and Cybersecurity

Cybersecurity is devoted to safeguarding the availability, privacy, confidentiality, and integrity of digital data stored and/or transmitted in any format. With daily attacks becoming sophisticated, cybersecurity protection through firewalls, intrusion detection systems, and other systems are becoming of utmost importance for individuals, businesses, and government alike. But as the degree of digitalization and connectivity increases, systems also become increasingly more susceptible to security vulnerabilities [24].

Wu et al. [17] highlight that the main role of cybersecurity in DM is to ensure the development, sharing and management of all product, process, and resource information digitally in a secure way. Thus, the security goal is three-fold. Confidentiality involves preventing sensitive data and information from being disclosed to unauthorized parties. Integrity involves maintaining the consistency, accuracy and trustworthiness of the data. Availability involves keeping data and resources available for authorized use.

Wu et al. [17] describe a scenario where design engineers develop an optimal product design (e.g., dimension, weight, and material) and attackers change the geometry parameters of a single part by gaining unauthorized access to the parts CAD model stored in a cloud environment. This attack results in invisible structural defects on critical features that cause product quality degradation with a significantly reduced service life or an unexpected catastrophic failure.

3.7. DM and Augmented Reality

Real-world interaction with the virtual world may make DM more practical, tacit, and applied. Augmented Reality (AR) is a technology that enables the overlay of virtual information onto the real world in real-time. This allows for user-based interaction, enabling virtual information (texts, images, sounds, etc.) rendered onto a real environment [25].

We divided the application of AR in DM tools into two main forms. First, AR is a means by which ideas are produced and modelled. The technology assists to produce what is seen in the digital model. The idea is built from the interaction of something real. Second, as scope AR supports the visualization of what has already been produced digitally. Applications for training, implementation and operationalization of processes developed through DM tools are examples of this.

Several key features of DM are related to decision-making and validation of both product, processes and resources. Thus, the main role of AR in DM is to provide an overlay of virtual information onto the real world in real-time, allowing fast, integrated and accurate decision-making. AR is used in many manufacturing life cycle phases, from assembly path simulation (process planning) to more complex tasks such as replacing physical manuals with augmented virtual contents (ramp-up for operation) [25].

For instance, Ong et al. [26] present a case that uses AR for assembly product design planning (PDP) and workplace design and planning (WDP), in order to improve the efficiency and quality of assembly design and planning at the early design stage. They discuss an AR assembly environment where engineers design, evaluate and plan product assembly and its sequence through manipulating virtual prototypes in a real workplace. Meanwhile, WDP information is fed back to designers and engineers in real-time for better decisions in assembly design and planning.

3.8. DM and Additive Manufacturing

Additive manufacturing (AM) is defined by a range of technologies that translate virtual model data into physical models or prototypes through a process of depositing successive layers of material of finite thickness. The more complex a product and its manufacturing operations are, the more valuable DM is.

The main role of AM in DM is to provide a fast and less costly way to create prototypes for physical simulation, in the path of DM tools to develop and test AM files to be printed. Not all models digitally developed are subject to digital testing, often because of their interaction with other parts or systems. DM benefits from AM by obtaining a faster and less costly way to create prototypes for physical simulations and analysis. These prototypes help identify failures and visualize necessary adaptations, avoiding future failures that can occur in the definitive productive process. Prototypes can be printed with precision, and adjustments can then be proposed that only would be noticed later on the actual manufacturing assembly.
line. This reduces the time and costs to develop a new model.

For instance, Renishaw [27] describes the use of DM tools to provide ready AM files through a case of hinge design, aligning virtual and real worlds of 3D design, test and analysis software, and metal 3D printing. As a result, the DM tools allowed printed parts to be produced more accurately, bringing lead time and material cost savings.

4. Discussion

Having presented the findings for each technology cluster, the DM application domain is presented next, in the context of Industry 4.0. This includes the DM tools and the technologies that can be used for its better use within each manufacturing life cycle phase, as well as contextualized how DM operates in this new industrial paradigm.

4.1. Application domain of DM in Industry 4.0

Studies, such as by Noh [28], present five manufacturing life cycle phases and the presence of DM tools in only three of them. However, the DM application domain was clearly expanded due to the new tools offered by DM solution providers and the rise of several new technologies that can be used jointly with DM. Thus, in this study, the manufacturing life cycle was divided into six phases as proposed by Mourtzis et al. [29] to better understand the function of DM tools. These phases are summarized in Fig. 1.

Fig. 1 also compiles the information provided in section three for the characterization of a coherent DM application domain in Industry 4.0. The framework presents three main set of information: manufacturing life cycle phases, the DM tools used in each phase, and the Industry 4.0 technologies that can be used with respective tools. Note that since DM is one of the technologies that fulfills the role of vertical and horizontal integration of organizational systems, it has been positioned at the base of the framework, interfacing with the various tools and technologies. The technologies are also listed in the framework alphabetically rather than by order of importance.

The classification is important because companies seeking DM capabilities do not acquire common software that provides all functionalities. Rather, the common business model features a platform that allows choosing only the tools desired. All tools do not have to be acquired, only those that are necessary for the ongoing manufacturing operation. The selection of the tools presented in the framework was based on offerings by key DM providers, such as Siemens with Tecnomatix [30] and Dassault Systèmes with Delmia [31].

4.2. Operating Digital Manufacturing in Industry 4.0

The second research question explores how DM operates in this new context. There is a new range of tools to help plan, integrate and simulate the manufacturing environment. Two key technology characteristics that stand out are integration and connectivity. Recent technological developments enable real-time integration and data acquisition and analysis, conditions to extrapolate from static to dynamic simulations, integrate systems with distinct characteristics, integrate real and digital factories, and control not only equipment but entire sites remotely. Systems and tools interoperability allows information management throughout the product life cycle, a main DM function, to be increasingly integrated. This, in turn, enables changes such as decentralized decision-making.

Regarding intra-organizational integration, in traditional (linear) project management, the product is developed and later its production and assembly processes are planned. Many organizations still have these areas working apart in silos. It
generates rework (and losses) due to difficulties of assembly, poor ergonomics, and unbalanced assembly lines. DM tools allow simultaneous engineering to be facilitated and optimized, preventing errors, anticipating corrections and creating nonlinear cascade effects.

Meanwhile, regarding inter-organisational integration, many organisations have used the strategy to focus on the core business, decentralize manufacturing operation, and digitize the supply chain. This increases flexibility and shortens time-to-market. For instance, companies that develop complex products with thousands of different parties have increasingly required that suppliers not only deliver a part within certain specifications and at the right time, but also deliver a digital product or process that enables traceability and simulations. One of the benefits of DM systems is breaking barriers by allowing agile manufacturing strategies to connect and integrate various parts of the manufacturing process. Digital integration with suppliers within a common platform allows the anticipation of several project phases. For instance, considering the manufacturing life cycle, the integration of suppliers allows the product assembly processes - through the use of digital mock-up tools - to be anticipated even before the parts are completely developed by the respective suppliers and requiring just a few changes when the part is finished. Teams working on process development, ergonomics, or manufacturing ramp-up can anticipate activities in their projects. Ensuring the sharing of quality data and information with all stakeholders is a key DM purpose and real-time information sharing with stakeholders is an important step for successful operations.

5. Conclusions, contributions and implications

This study offered a new framework defining the current application domain composed by DM tools and technologies used in each manufacturing life cycle phase. Many of the technologies are not new, but recent forms of integration, improvements in use, and joint use have changed the field as a whole, opening up several new opportunities. Presenting a clear and well-defined application domain is important to create, plan and conduct successful DM adoption projects. Also, as discussed, due to technological changes the way DM is used has changed dramatically over the last few years, creating a dynamic environment to design, redesign and analyse the factory, the product and the manufacturing process.

The study while contributing to a better understanding of DM is restricted to the nine technologies presented in the selected framework although more technologies exist. Exploring the research questions in this paper will assist our future research efforts on defining a framework for DM adoption. This will contribute to better understand how technology changes affect operational and organizational strategies and conditions.

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