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Reviewing Digital Manufacturing concept in the Industry 4.0 paradigm

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Abstract

Digitalization of manufacturing is once again on the industry application research agenda and Digital Manufacturing plays a fundamental role in this process. However, there is a lack of commonality in the literature about the purpose of Digital Manufacturing. The purpose of this paper is to analyze the concept and application domain of Digital Manufacturing considering the increasingly established Industry 4.0 paradigm. Based on a content analysis concepts are framed, and new technological characteristics identified. The paper contributes to a better understanding of the future challenges that companies face by positioning Digital Manufacturing conceptually and delimiting its application domain.

Keywords: Digital Manufacturing; Digital Factory; Industry 4.0; Smart Manufacturing; Manufacturing life cycle.

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, robotics, additive manufacturing, and human-machine interaction, are unleashing innovations that change the nature and content of manufacturing itself [1–3].

Recently, emerging technologies have game-changing impacts on manufacturing models, approaches, concepts, and even businesses. The term Industry 4.0 incorporates emerging technical advancement to improve industry so as to deal with some global challenges that is oriented towards digital and virtual technologies and it is driven by real-time data interchange and flexible manufacturing, enabling customized production [4–7]. Being Digital Manufacturing (DM) under the umbrella of Industry 4.0 technologies, Hartmann et al. [1] points out that industry leaders agree that digital manufacturing technologies will transform all aspects in the manufacturing systems of value chains.

Digital Manufacturing technology 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

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manufacturing industry [9,10]. Manufacturing becoming increasingly multidisciplinary was perhaps inevitable. From the combination of organizational sciences, such as Lean Manufacturing, Total Quality Management - TQM, and Concurrent Engineering; with engineering science of CIM emerged the concept of digital manufacturing that highlighted the need for more collaborative product and process design [10,11].

Although not a recent issue, two aspects are noted in the digital manufacturing literature. First, the definition and uniqueness of digital manufacturing remains unclear. The multiple definitions of digital manufacturing converge to the central idea of manufacturing improvement using technology integration. However, there is a noticeable difference in this convergence and the application domain. There is also a common view of digital manufacturing as being synonymous to 'digital factory'. The lack of a clear definition of digital manufacturing related concepts is problematic since it makes communication less effective among researchers, and more difficult to plan, design and implement digital manufacturing initiatives for managers. Second, it remains unclear how Industry 4.0 aspects influence digital manufacturing, and whether technological changes influenced its use. Thus, this study aims to explore the meaning of Digital Manufacturing in the context of Industry 4.0. To answer these questions a systematic literature review was conducted. Through content analysis of scientific and technical papers, various Digital Manufacturing concepts were assessed.

The study is organized as follows. Section 2 presents the research design on method used to collect and analyze the data, including criteria for sample selection and content analysis. Section 3 covers the characteristics of digital manufacturing systems and their role in the manufacturing life cycle. Section 4 discusses and presents answers to the research question, proposing a broad definition of digital manufacturing and systematically evaluates the differences in purpose, emphasis and benefits in relation to 'digital factory'. Finally, Section 5 presents the conclusions, contributions, and implications for theory and practice.

2. Research design

The research strategy is based on a systematic literature review. It provides a comprehensive view of existing research and contributions, and points to future research. The selected papers are studied through the lens of content analysis, as proposed by Bardin [12], to compile the identified concepts. The software Atlas TI® was used to conduct the analysis. Results was based on coding of text, frequency of words, and words relationship.

In a recent literature review on Digital Manufacturing, Shinohara et al. [13] note that the most relevant studies on this topic are recovered from journals in the Science Direct database. The search terms we selected to use were 'digital manufacturing' and 'digital factory', because they are often used as synonyms both in academic and technical documents. The first search attempt was made in the database considering the terms in all fields resulting in 1140 papers. A second attempt was made limiting the results to articles whose terms appear in the title or keywords. This search resulted in 93 papers. This set of papers were further filtered if: (i) there are authors' own definitions for 'digital manufacturing' or 'digital factory'; or (ii) there are definition and concepts cited and/or adopted by the authors on 'digital manufacturing' or 'digital factory', which are traceable to their sources. The select papers were added to the systematic literature review portfolio, and their references scrutinized for tracing DM concepts. This snowballing technique is similar to snowball sampling as presented by Goodman [14] in sociology research, it is typically used to find cited references. It consists of searching papers listed in references of select papers, and thereby growing the sample. The new papers that fulfill the previously set criterion are added to the portfolio, as recommended by Sayers [15]. Fig. 1 illustrates the search strategy using the PRISMA diagram flow[16].

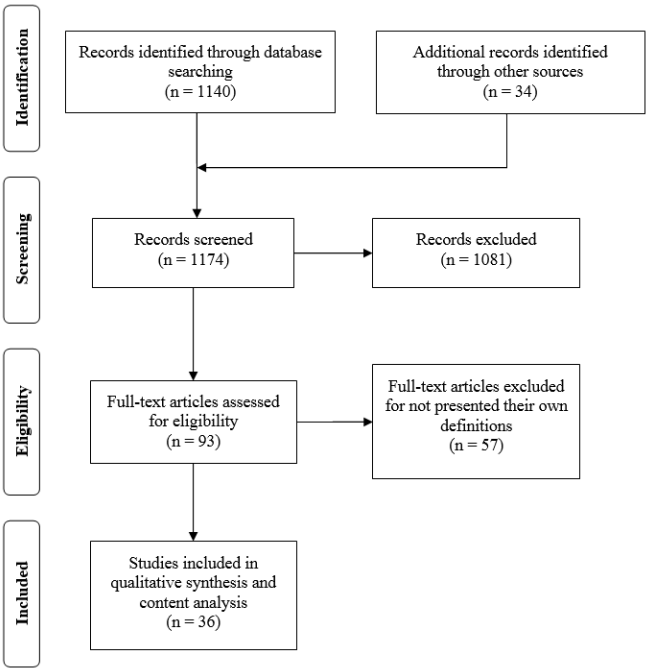

Fig. 1. Search strategy and studies selection (PRISMA flow diagram).

The first phase selected among the 93 papers those that presented their own definitions. 20 of them met the criteria and were directly added to the paper set. The second phase applied the snowball technique to these 93 papers. This process resulted in 34 new papers to be analyzed. From these, 16 presented their own definitions and were included in the paper set. Thus, the final portfolio used for the literature review and content analysis contains 36 papers.

3. Results

Since there is a key terminology confusion between "Digital Factory" and "Digital Manufacturing", we started by analyzing definitions proposed by several authors. The review of Digital Factory definitions resulted in 23 different and original definitions. A great concentration of several terms used to define Digital Factory existed. Some terms are not quoted exactly as presented here, but contextually they have

similar meanings (e.g. simulation, simulations, simulate) and were clustered for analytical purposes when possible. Each of the 23 definitions used at least one of these terms. Terms that primarily define characteristics or function are compiled on Table 1.

Table 1. Most used terms to define Digital Factory.

Term	Author(s) using term
PPR (Product, Process and Resources)	Wenzel, Jessen, and Bernhard 2005 [17]; Zülch and Grieger 2005 [18]; Bracht and Masurat 2005 [19]; Kuehn 2006 [20]; Pakkala and Lopez 2006 [21]; Ŝtefánik et al. 2008 [22]; Zhao et al. 2009 [23]; Kjellberg et al. 2009 [24]; Gregor et al. 2009 [25]; Cheutet et al. 2010 [26]; Azevedo and Almeida 2011 [27]; Polášek, Bureš, and Šimon 2015 [28].
Digital model	Wiendahl, Harms, and Fiebig 2003 [29]; Wenzel, Jessen, and Bernhard 2005 [17]; Zülch and Grieger 2005 [18]; Bracht and Masurat 2005 [19]; Ŝtefánik et al. 2008 [22]; Kjellberg et al. 2009 [24]; Gregor and Medvecký 2010 [30]; Cheutet et al. 2010 [26]; Azevedo and Almeida 2011 [27]; Malak and Aurich 2013 [31]; Shariatzadeh et al. 2016 [32].
Support	Wenzel, Jessen, and Bernhard 2005 [17]; Zülch and Grieger 2005 [18]; Kuehn 2006 [20]; Butala et al. 2008 [33]; Gregor and Medvecký 2010 [30]; Zuehlke 2010 [34]; Cheutet et al. 2010 [26]; M. Matsuda, Kashiwase, and Sudo 2012 [35]; Constantinescu et al. 2014 [36]; Polášek, Bureš, and Šimon 2015 [28].
Simulation	Wiendahl, Harms, and Fiebig 2003 [29]; Pakkala and Lopez 2006 [21]; Zhao et al. 2009 [23]; Gregor and Medvecký 2010 [30]; Zuehlke 2010 [34]; Cheutet et al. 2010 [26]; Azevedo and Almeida 2011 [27]; M. Matsuda, Kashiwase, and Sudo 2012 [35]; Dombrowski and Ernst 2013 [37]; Matsuda et al. 2016 [38].
Tools	Wenzel, Jessen, and Bernhard 2005 [17]; Zülch and Grieger 2005 [18]; Kjellberg et al. 2009 [24]; Zuehlke 2010 [34]; Cheutet et al. 2010 [26]; Azevedo and Almeida 2011 [27]; Malak and Aurich 2013 [31]; Constantinescu et al. 2014 [36]; Polášek, Bureš, and Šimon 2015 [28].
Production planning	Zülch and Grieger 2005 [18]; Bracht and Masurat 2005 [19]; Kuehn 2006 [20]; Pakkala and Lopez 2006 [21]; Ŝtefánik et al. 2008 [22]; Gregor et al. 2009 [25]; Polášek, Bureš, and Šimon 2015 [28]; Matsuda et al. 2016 [38].
Integration	Kuehn 2006 [20]; Ŝtefánik et al. 2008 [22]; Zhao et al. 2009 [23]; Gregor et al. 2009 [25]; Gregor and Medvecký 2010 [30]; Zuehlke 2010 [34]; Azevedo and Almeida 2011 [27].
Design	Kuehn 2006 [20]; Ŝtefánik et al. 2008 [22]; Butala et al. 2008 [33]; Zhao et al. 2009 [23]; Cheutet et al. 2010 [26]; Azevedo and Almeida 2011 [27]; Shariatzadeh et al. 2016 [32].
Production system	Bracht and Masurat 2005 [19]; Kjellberg et al. 2009 [24]; Gregor and Medvecký 2010 [30]; Zuehlke 2010 [34]; M. Matsuda, Kashiwase, and Sudo 2012 [35]; Shariatzadeh et al. 2016 [32].
Data	Westkämper and von Briel 2001 [39]; Ŝtefánik et al. 2008 [22]; Gregor et al. 2009 [25]; Azevedo and Almeida 2011 [27].
Factory planning	Wenzel, Jessen, and Bernhard 2005 [17]; Zuehlke 2010 [34]; Constantinescu et al. 2014 [36].
ERP	Ŝtefánik et al. 2008 [22]; Gregor et al. 2009 [25]; Zuehlke 2010 [34].

Meanwhile, the review of Digital Manufacturing definitions resulted in 13 different and original definitions. Analyzing these definitions, we found a concentration of terms that define it. Again, some terms were clustered for analytical purposes. Each of the 13 definitions used at least one of these terms. Terms that primarily define characteristics or function are compiled on Table 2.

Table 2. Most used terms to define Digital Manufacturing.

Term	Author(s) using term
PPR (Product, Process and Resources)	Maropoulos 2003 [40]; Curran et al. 2007 [41]; Butterfield et al. 2007 [42]; Nylund, Salminen, and Andersson 2007 [43]; Filho et al. 2009 [44]; Chryssolouris et al. 2009 [45]; Coze et al. 2009 [9]; Menéndez et al. 2012 [46]; Al-Zaher and ElMaraghy 2014 [47].
Data	Maropoulos 2003 [40]; Curran et al. 2007 [41]; Mahesh et al. 2007 [48]; Butterfield et al. 2007 [42]; Filho et al. 2009 [44]; Al-Zaher and ElMaraghy 2014 [47].
Production planning	Butterfield et al. 2007 [42]; Chryssolouris et al. 2009 [45]; Coze et al. 2009 [9]; Lee, Han, and Yang 2011 [49]; Lee et al. 2016 [50].
Simulation	Butterfield et al. 2007 [42]; Filho et al. 2009 [44]; Coze et al. 2009 [9]; Menéndez et al. 2012 [46]; Al-Zaher and ElMaraghy 2014 [47].
Design	Nylund, Salminen, and Andersson 2007 [43]; Butterfield et al. 2007 [42]; Coze et al. 2009 [9]; Menéndez et al. 2012 [46]; Al-Zaher and ElMaraghy 2014 [47].
Tools	Westkämper 2007 [51]; Nylund, Salminen, and Andersson 2007 [43]; Filho et al. 2009 [44]; Coze et al. 2009 [9]; Lee, Han, and Yang 2011 [49]; Menéndez et al. 2012 [46].
PLM/PDM	Maropoulos 2003 [40]; Curran et al. 2007 [41]; Filho et al. 2009 [44]; Chryssolouris et al. 2009 [45]; Menéndez et al. 2012 [46].
Integration	Curran et al. 2007 [41]; Butterfield et al. 2007 [42]; Nylund, Salminen, and Andersson 2007 [43]; Lee, Han, and Yang 2011 [49].
Information management	Maropoulos 2003 [40]; Curran et al. 2007 [41]; Butterfield et al. 2007 [42]; Filho et al. 2009 [44].
Integrated environment	Butterfield et al. 2007 [42]; Filho et al. 2009 [44]; Coze et al. 2009 [9].
Validation	Chryssolouris et al. 2009 [45]; Coze et al. 2009 [9].

Comparing the two tables, the intersection of terms that are used to define both terminologies are found, while some terms are used to define only one of them. Fig. 2 shows a network based on this content analysis.

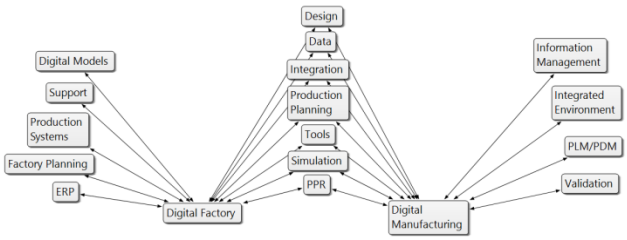

Fig. 2. Content analysis result.

The network shows that both Digital Factory and Digital Manufacturing definitions have congruence in some areas by presenting similar characteristics. This reinforces the terminology confusion. The congruence is mainly related to the object that both technologies are used: Product, Process and Resources (PPR). An intersection was visualized in relation to integration of data (of PPR) and tools (for PPR), and both use the simulation for one of the common purposes, production planning. However, some characteristics are unique. More than half of the authors who originally defined digital factory use 'digital models' or similar terms, while only one author uses this to characterize digital manufacturing. On integration, the authors that define digital factory cite integration between CAD, MES and ERP systems. This means a focus on the integration of digital models (CAD) to production management systems (ERP and MES), while the integration cited for the definition of Digital Manufacturing uses PDM/PLM systems, that is, an information management approach during the whole product life cycle. The differences may appear minor, but they are crucial for the understanding of technology use and enterprise integration.

4. Discussion

This study sought to identify how digital manufacturing is defined considering the new paradigm of Industry 4.0. In 2005, Dalton-Taggart [52] stated that "technology improvements are making digital manufacturing real to many, and many companies are using pieces of digital manufacturing without realizing it". This appears to remain true. And as cited by Coffey [53], when asked a group of manufacturing staff to describe what digital manufacturing is and how it works, they are likely to emphasize different areas based on their experience and specific job responsibilities.

Although there is a coherence of purpose in the original DM definitions, there is no inclusive and definitive definition. Each author defines DM in a coherent way for his or her research, but without comprehensive coverage of other definitions or views. Most definitions found in the early years cover only modeling, digitization and information management [40–42,48]. In recent years, definitions have become broader, with the inclusion of decision making considerations, citing the potential for more collaborative environments and interoperability, benefits also sought by the inclusion of industry 4.0 technologies. Hence, and based on the analysis presented in Section 3, the concept of digital manufacturing can be synthesized as such:

> "Digital manufacturing is a set of tools used for information management that assists decision-making throughout the manufacturing life cycle. Based on computer integrated systems, simulation, information-sharing models and collaboration tools to design, redesign and analyze the factory, the product and the manufacturing process in an integrated way. It is often integrated by Product Life cycle Management (PLM) systems and interfaces and makes use of legacy systems such as Enterprise Resource Planning (ERP), Manufacturing Execution Systems (MES) and Supply Chain Management (SCM)".

It is also important to identify what DM is not and how terms often used as synonyms differ from each other. A SLR was conduct to identify the key differences between "Digital Factory" (DF) and "Digital Manufacturing". The results show that "Digital Factory" is the technology to capture and represent information to model production systems and available processes in a factory [18,29,31,32,39]. It is concerned with representing a digital model of resources and processes available in the factory to improve the physical aspects of manufacturing and support factory planning, as layout and material flow studies. Meanwhile, 'Digital Manufacturing' extrapolates this concept since it can use the representation of the product and process in a digital way, but its main concern remains in integrating technologies and business areas focusing on improving the entire product life cycle. This ability to connect different parts of the product life cycle through digital data that carries design intent and management information, and utilizes that information for intelligent automation and smarter, more efficient business decisions is the actual role of Digital Manufacturing [8].

DM encompasses a whole range of evolving tools, largely developed in silos. Only recently have manufacturers realized the benefits of connecting and integrating the different DM elements. Several technologies that support digital manufacturing are quite well established and commonly used. But combined and integrated use, as well as the possibility of real-time application, creates many new possibilities for industry application. Although DM and DF have a few characteristics in common, as seen in Fig. 2, the former is not an evolution or extension of the latter. The two have different purposes and can even favorably be used in parallel. Table 3 describes terminologies and differentiations on emphasis and key benefits.

Table 3. Comparison of terms.

	Digital Factory	Digital Manufacturing
Description	Technology to capture and represent information to model manufacturing systems and available processes in a factory	A set of tools used for information management that assists decision-making throughout the manufacturing life cycle. Based on computer integrated systems, simulation, information-sharing models and collaboration tools to design, redesign and analyze the factory, the product and the manufacturing process in an integrated way
Emphasis	To represent all relevant information about the resources in the factory and their processes	To integrate technologies and departments focusing on better performance and decision-making throughout the product life cycle
Key Benefits	To develop and to improve all aspects of the factory until the physical manufacturing of a product meets the quality, time and cost requirements	To faster production ramp-up and time-to-market, increase in flexibility, shorter product development, errors reduction, decreasing cost and time, besides increasing quality

In answering the research question, a comprehensive definition of Digital Manufacturing is proposed, which explains the differences in content, emphasis and benefits with 'digital factory', a terminology often cited as a synonym. This differentiation is essential to understand the purpose of each technology.

5. Conclusions, contributions and implications

According to PMI® [54] a well-defined project scope enables managers to allocate accurately the resources to successfully complete a project. In this way, the study results directly contribute to solving part of this issues. It presents a contextualized definition based on the main DM characteristics. This is important because: (i) the presence of well-defined terms contribute to the evolution of DM body of knowledge and mitigates poor communication or misinterpretation; (ii) presenting a clear and well-defined application is essential to create, plan and conduct successful DM implementations.

It was also discussed the influence of Industry 4.0 on digital manufacturing. Due to technological changes the way DM is used has changed dramatically over the last few years. Many of the technologies are not new, but recent forms of integration, improvements in use, and joint use, have changed the DM field as a whole, opening up several new challenges and opportunities.

Exploring the research questions in this paper will assist our future research efforts on defining critical success factors and identifying DM implementation enablers and barriers. This will contribute to better understand how technology changes affect operational and organizational strategies and conditions.

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