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ELIAS HANS DENER RIBEIRO DA SILVA

TOWARDS DIGITAL MANUFACTURING IN INDUSTRY 4.0

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2018

ELIAS HANS DENER RIBEIRO DA SILVA

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Thesis dissertation presented to the Industrial and Systems Engineering Graduate Program of the Pontifical Catholic University of Parana in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Industrial and Systems Engineering.

Supervisor: Prof. Dr. Edson Pinheiro de Lima.

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Curitiba, 10th December of 2018.

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Curitiba, 10 de dezembro de 2018.

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“Wherever we are, our home is in our mind”

Chino Vietcong

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ABSTRACT

The digital revolution is in many ways driving industry transformations. Digital Manufacturing (DM) is increasingly important in this technological scenario as one of the knowledge areas within the Industry 4.0 agenda. DM stands out by combining conventional manufacturing technologies with digital techniques for modelling and analysis of the product, the process, and the production system. Although DM is a subject of growing relevance in the global technology scenario, it is still far from being a highly mature subject that presents a consolidated content base and a clear definition of the scope, both in terms of implementation and use. There is a lack of commonality in literature, which makes prohibits communication between authors as well as evolution of the research. It also makes it difficult for companies planning their implementation processes and the commissioning of technologies and tools. This research defines DM characteristics in the current industrial scenario, incorporating the paradigm of Industry 4.0 and provides a developed framework for DM implementation and later use. A multimethod research approach is adopted consisting of three main parts: (i) a systematic literature review and content analysis to analyze the concept and application domain of DM in Industry 4.0, covering manufacturing life cycle phases, DM tools used in each phase, and Industry 4.0 technologies used with respective tools; (ii) a survey of 113 users, managers, implementers and researchers working on DM and Industry 4.0 that identifies the critical factors for the technology implementation and use; and (iii) six cases studies placing these factors into a framework that helps guide organizations towards DM in Industry 4.0. As a result, a meta-framework with six distinct phases is proposed with critical success factors noted per phase. It also defines deliverables of each phase for a DM implementation process and later use. As such, this research conceptually develops DM theory and methods in the new industrial context, while empirically it contributes to the planning and executing of DM implementation, operational use, and management of both.

Keywords: Digital manufacturing, Industry 4.0, implementation process, advanced manufacturing technologies, manufacturing life cycle.

RIBEIRO DA SILVA, Elias H. D. Towards Digital Manufacturing in Industry 4.0. Curitiba, 2018, 203p. Tese de doutorado – Programa de Pós-Graduação em Engenharia de Produção e Sistemas, PUCPR, 2018.

RESUMO

A revolução digital está impulsionando as transformações da indústria em muitos aspectos. A Manufatura Digital (MD) é cada vez mais importante neste cenário tecnológico como uma das áreas de conhecimento dentro da agenda da Indústria 4.0. A MD destaca-se pela combinação de tecnologias convencionais de manufatura com técnicas digitais para modelagem e análise do produto, do processo e do sistema de produção. Embora a MD seja um assunto de crescente relevância no cenário tecnológico global, ainda está longe de apresentar um conteúdo consolidado e uma definição clara do escopo, tanto em termos de implementação quanto de uso. Há uma falta de concordância na literatura, dificultando a comunicação entre os autores. Isso também torna difícil para as empresas planejarem seus processos de implementação e o comissionamento de tecnologias e ferramentas. Esta pesquisa define as características da MD no cenário industrial atual, incorporando o paradigma da Indústria 4.0 e fornece um framework para implementação e uso da MD. Uma abordagem de pesquisa multimétodo é adotada consistindo de três partes principais: (i) uma revisão sistemática de literatura e análise de conteúdo para analisar o conceito e domínio de aplicação do DM na Indústria 4.0, cobrindo fases do ciclo de vida de fabricação, ferramentas de MD usadas em cada fase e tecnologias da Indústria. 4.0 utilizadas em conjunto; (ii) survey com 113 usuários, gerentes e pesquisadores que trabalham diretamente com MD e Indústria 4.0 para identificação de os fatores críticos para a implementação e uso da tecnologia; e (iii) estudo de caso com seis multinacionais para estruturar os fatores em um framework que ajude as organizações a buscarem uma MD nos conceitos da Indústria 4.0. Como resultado, um meta-framework com seis fases distintas é proposto com fatores críticos de sucesso observados por fase. Ele também define as entregas de cada fase para um processo de implementação e uso da MD. Assim, esta pesquisa conceitualmente desenvolve teoria e métodos de MD no novo contexto industrial, enquanto empiricamente contribui para o planejamento e execução da implementação da MD, assim como seu uso operacional e gerenciamento.

Palavras-chave: Manufatura Digital, Indústria 4.0, processo de implementação, tecnologias avançadas de manufatura, ciclo de vida da manufatura.

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ABBREVIATIONS

CE	Concurrent Engineering
CIM	Computer-integrated manufacturing
CPS	Cyber-Physical Systems
CRM	Customer Relationship Management
DF	Digital Factory
DFM	Design for Manufacturing
DM	Digital Manufacturing
ERP	Enterprise Resource Planning
IoS	Internet of Services
IIoT	Industrial Internet of Things
IoT	Internet of Things
JIT	Just in Time
LP	Lean Production
MES	Manufacturing Execution Systems
PLM	Product Lifecycle Management
RSB	Risk Breakdown Structure
SCM	Supply Chain Management
SME	Small and Medium-sized Enterprises
TQM	Total Quality Management
SF	Smart Factory
SLR	Systematic Literature Review
SM	Smart Manufacturing

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1 INTRODUCTION

During the 20th century, a major innovation in consumer industries was the elevation of products from mere commodities to differentiated brands. In the 21st century, it is the digital revolution that is driving the transformation of consumer industries. Major demographic, technology and ecosystem trends are propelling this transformation, creating new risks and opportunities for consumer businesses. This digital revolution is now breaching the walls of manufacturing as it continues to disrupt media, finance, consumer products, healthcare, and other sectors. Indeed, the explosion in data and new computing capabilities - along with advances in other areas such as artificial intelligence, automation and robotics, additive technology, and human-machine interaction - are unleashing innovations that are changing the nature of manufacturing itself. Industry and academic leaders agree that digital manufacturing technologies will transform all aspects in the manufacturing value chain (Hartmann, King, & Narayanan, 2015; World Economic Forum, 2016).

Almada-Lobo (2016) observes that 'Industry 4.0' - also known as 'The 4th Industrial Revolution' - is being predicted, therefore allowing companies to take specific actions before it happens. This revolution is based on the concepts of CPS - Cyber-Physical Systems (a fusion of the physical and the virtual worlds), the Internet of Things (IoT) and the Internet of Services (IoS). This scenario is already changing several aspects of manufacturing companies.

Digital manufacturing (DM) is a subject that is becoming highly relevant in the global technological scenario as one of the areas of knowledge within the Industry 4.0 agenda. Digital manufacturing evolved from manufacturing initiatives such as design for manufacturability (DFM), computer-integrated manufacturing (CIM), flexible manufacturing, lean manufacturing and others that highlight the need for more collaborative product and process design (Siemens, 2018).

Digital Manufacturing is a set of integrated, cross- cutting enterprise-level smart-manufacturing approaches, leveraging the current advances in information technology systems and tools to achieve error-free manufacturing of products and components. This enables the provision of services that support manufacturing in a broad sense. Services enabled by DM platforms are associated to collecting, storing, processing and delivering data, describing the manufactured products, processes, and assets that make manufacturing happen (EFFRA, 2016; President's Council of Advisors on Science and Technology, 2014).

1.1 Description of the problem and research gaps

Digital manufacturing is a subject of growing relevance in the global technology scenario, but it is still far from being a highly mature subject that presents a consolidated content base and a clear definition of the scope, both in terms of implementation and use. Several definitions of digital manufacturing converge to the central idea of manufacturing improvement using technology integration, but there is a noticeable difference in coverage and application scope among them. Many of these definitions limit digital manufacturing simply to development, analysis, and visualization in three dimensions while other authors suggest an extended integration with factory floor systems or even Industry 4.0 technologies, such as IoT devices, resources that were scarce (or non-existent) when discussions about digital manufacturing began. In addition, there is a constant mention of digital manufacturing being synonymous of “digital factory", "smart factory" or even "smart manufacturing".

The lack of a clear definition of the digital manufacturing theme academically, as occurs with other classical research topics, makes communication among authors and the evolution of the theme within a consolidated content base difficult. Inside the companies, the consequences of this problem are even worse, since this lack of clarity makes it difficult to plan the implementation of a project, obtain human and financial resources or develop capabilities for proper use of the tools. In the case of high-cost resources this becomes critical.

In addition, despite the growth of publications on the subject of digital manufacturing, with several publications about technologies related (Azevedo & Almeida, 2011; Butterfield et al., 2010; Chien, Gen, Shi, & Hsu, 2014; Dombrowski & Ernst, 2013; Dulina & Bartanusova, 2015; Filho et al., 2009; Hincapié, de Jesús Ramírez, Valenzuela, & Valdez, 2014; N. Shariatzadeh, Sivard, & Chen, 2012), some researches regarding content models (Bracht & Masurat, 2005; Rohrlack, 2008; Stef, Draghici, & Draghici, 2013; Wenzel, Jessen, & Bernhard, 2005), a few case studies (A. Caggiano & Teti, 2012; Alessandra Caggiano, Caiazzo, & Teti, 2015; Fonseca, 2013; Kim, Lee, Park, Park, & Jang, 2002; Vidal, Kaminski, & Netto, 2009), there is a lack of in-depth studies of the implementation process in companies.

Although there is a relevant mass of information about DM concept and DM applied technologies, there is still scarce information of the implementation process and the influence of the new aspects from Industry 4.0. Projects show there is an implicit difficulty in the conduction of digital manufacturing projects since it is not a simple adoption of new technologies but a project that requires a real change in organizational culture, aimed at integrating processes and silos.

The lack of a framework to guide the implementation process, providing the macro steps and their unfolding, the critical success factors in each stage of implementation and use, and the risks involved in the process cause a disproportionate effort and a process of "trial and error" not suitable for companies seeking to be competitive in the market.

1.2 Research questions

The main purpose of this research is to develop a framework to guide the implementation and use of digital manufacturing in an Industry 4.0 context. For this, four specific objectives (SO) are established, representing important steps in the development of the study. Based on the objectives presented, the main research question emerges: “What is the role of digital manufacturing in the context of industry 4.0?”. Complementary RQs are defined based on the fact that the concept of digital manufacturing is still misunderstood both in the academia and companies. There is a need to concretely understand and fully describe the research object, and only then to develop a framework. To achieve this purpose some additional research questions (RQ) have been formulated, as indicated in Table 1.

Table 1 - Research questions and research objectives

Specific objectives (SO)	**Research question (RQ)**
SO1 – Characterize and define content and scope of the application of digital manufacturing in Industry 4.0	RQ1: What is the scope of application of Digital Manufacturing in Industry 4.0 and what differs it from other concepts?
SO2 – Identify how Industry 4.0 technologies are influencing digital manufacturing	
SO3 – Define the critical success factors for the implementation and use of digital manufacturing in an Industry 4.0 context	RQ2: What are the critical success factors for the implementation and use of digital manufacturing in Industry 4.0?
SO4 - Develop an appropriate framework for the implementation and use of digital manufacturing in an Industry 4.0 context	RQ3: How to conduct the implementation and management process of digital manufacturing in Industry 4.0?

The first objective is completed through a systematic literature review and a content analysis that both assists and examines the research field about DM by the bibliometric analysis and define how the Industry 4.0 principles and technologies are influencing DM

The second objective is accomplished by a multimethod approach, that includes content analysis, preliminary case study in a large automotive company and a survey conducted with 113 specialists in DM and Industry 4.0, including researchers, users, managers and consultants. The factors were identified and studied, and for each factor, a categorization is proposed, and a conceptual framework is introduced.

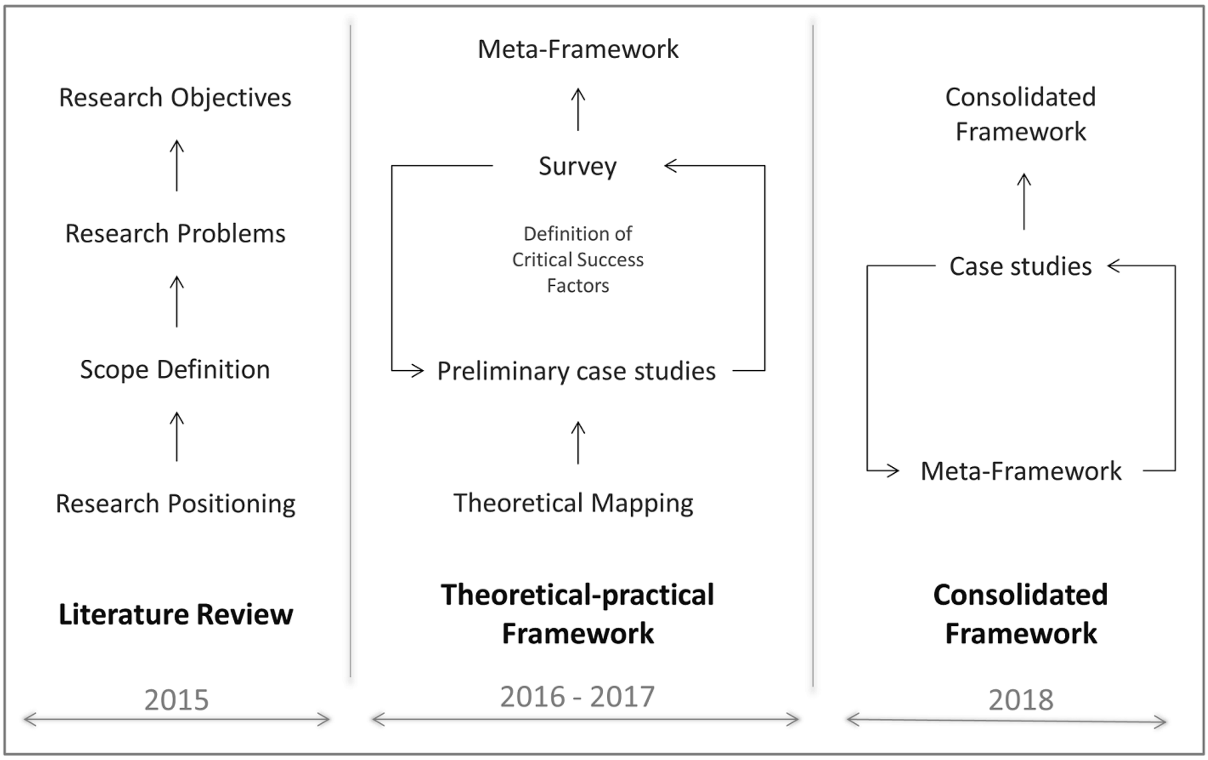
The fourth objective is completed through case studies performed with several organizations investigating and reviewing the set of factors and the underling logic of implementation and use in practice.

Considering this whole picture, this research contributes in the following areas: (1) digital manufacturing conceptualization; (2) digital manufacturing implementation and management; (3) manufacturing systems; (4) operations management.

1.3 Research chronology and structure

The research was conducted in three main phases. Multiple research methods that connect and configure the search for answers were used, which are illustrated in Figure 1.

Figure 1 - Research planning



As can be seen in Figure 1, first phase focuses on literature review, to guarantee that the research fills gaps in theory and practice. Second phase focuses in developing a theoretical-practical framework, developed through agents' agreement, but not revised in practice. Third phase focuses in developing a consolidated framework, revising in practice the variables and the proposed framework. Figure 1 illustrates how each phase is construct moving from, for instance, the literature review through various stages to the research objective.

This thesis is structured in stages that will be represented by scientific papers and technical reports, each one seeking to answer a set of RQs and to fulfill specific objectives presented in Table 2.

Table 2 - Research outputs

Phase	RQ	Outputs	Journal/Conference	Classification	Year
Literature Review	RQ1	Analysis of studies on digital manufacturing: a literature review *(in Portuguese "Análise de estudos na área de manufatura digital: uma revisão da literatura")*	Production Engineering Symposium	Conference paper	2015
	RQ1	Reviewing Digital Manufacturing concept in the Industry 4.0 paradigm	Revista IEEE América Latina *(in process of submission)*	Q1 – IF 0.502	2019
	RQ1	Operating Digital Manufacturing in Industry 4.0: the role of advanced manufacturing technologies	International Journal of Advanced Manufacturing Technology *(under review)*	Q1 – IF 2.601	2018
Theoretical-practical framework	RQ2	Critical Success Factors for Digital Manufacturing Implementation in the Context of Industry 4.0	2015 Industrial and Systems Engineering Research Conference	Conference paper	2015
	RQ2	Digital manufacturing as part of digital transformation in Renault's assembly plants *(in Portuguese "A manufatura digital como parte da transformação digital das fábricas de montagem Renault")*	*n/a*	Technical report	2016
	RQ2	Implementation of digital manufacturing in Renault's assembly plants *(in Portuguese "A implementação da manufatura digital em fábricas de montagem Renault")*	*n/a*	Technical report	2017
	RQ2	Supplier integration through Digital Manufacturing: a SME paradox	International Symposium on Supply Chain 4.0	Conference paper	2018
	RQ2	In pursuit of Digital Manufacturing	Procedia Manufacturing Journal	Conference paper	2018
Consolidated framework	RQ3	Towards Digital Manufacturing in Industry 4.0: a comprehensive framework	Journal of Manufacturing Technology Management *(under review)*	Q1 – IF 2.194	2018

Table 2 indicates two classifications for the journals, first by SCImago rank (divided in quartiles Q1, Q2, Q3, and Q4 - whereof Q1 is the highest quality and Q4 is the lowest quality) and the Impact Factor from the Journal Citation Reports. Also, the year of publication or submission is indicated. All papers under review are indicated. Table 3 briefly presents the summary of the authors' contributions for the five appended papers in this thesis.

Table 3 - Authors' contributions to the appended papers

Appended papers	Order of authors	Authors' contributions
Paper 1	Shinohara, Rocha, **Ribeiro da Silva**, Pinheiro de Lima, Deschamps	Shinohara, Rocha and Ribeiro da Silva selected the sample, collected and analyzed the data, and wrote the paper. Pinheiro de Lima contributed helping to design the study and in discussion section refining arguments and better structuring the text. Deschamps contributed with insights throughout writing phase.
Paper 2	**Ribeiro da Silva**, Shinohara, Pinheiro de Lima, Angelis	Ribeiro da Silva planned the study, selected the sample, and was the main author writing all sections. Shinohara contributed by analyzing the data sample. Pinheiro de Lima and Angelis helped better structuring the paper and providing insights throughout the writing phase.
Paper 3	**Ribeiro da Silva**, Shinohara, Angelis, Pinheiro de Lima	Ribeiro da Silva planned the study, proposed the theoretical framework and was the main author writing all sections. Shinohara contributed by selecting and analyzing the data sample. Angelis contributed helping to develop and to refine the theoretical framework. Pinheiro de Lima and Angelis contributed in refining arguments and structuring the text to a more academic standard.
Paper 4	**Ribeiro da Silva**, Angelis, Pinheiro de Lima	Ribeiro da Silva developed the research design, conducted the entire survey process, analyzed data, and was the main author writing all sections. Angelis contributed extensively writing in all section, refining arguments and structuring the text. Pinheiro de Lima contributed helping clarifying literature, research design, discussion and conclusions.
Paper 5	**Ribeiro da Silva**, Angelis, Pinheiro de Lima	Ribeiro da Silva developed the research design, selected appropriate sample, conducted the interviews, analyzed data, proposed the theoretical framework and was the main author writing all sections. Angelis and Pinheiro de Lima contributed in refining arguments and structuring the text to a more academic standard.

1.4 Overview of thesis document

The document is organized in five chapters: the introduction, the theoretical foundation, the research design, the findings and conclusion. The introduction chapter explores the problem definition and research gaps, define research questions and research objectives, and define the chronology and structure for the research. The second chapter presents the theoretical foundation that contextualize the research topic and supports the comprehension of the research gaps and opportunities of study. After that, the research design explains the three phases and the research stages developed as well as the research details and the methods are presented.

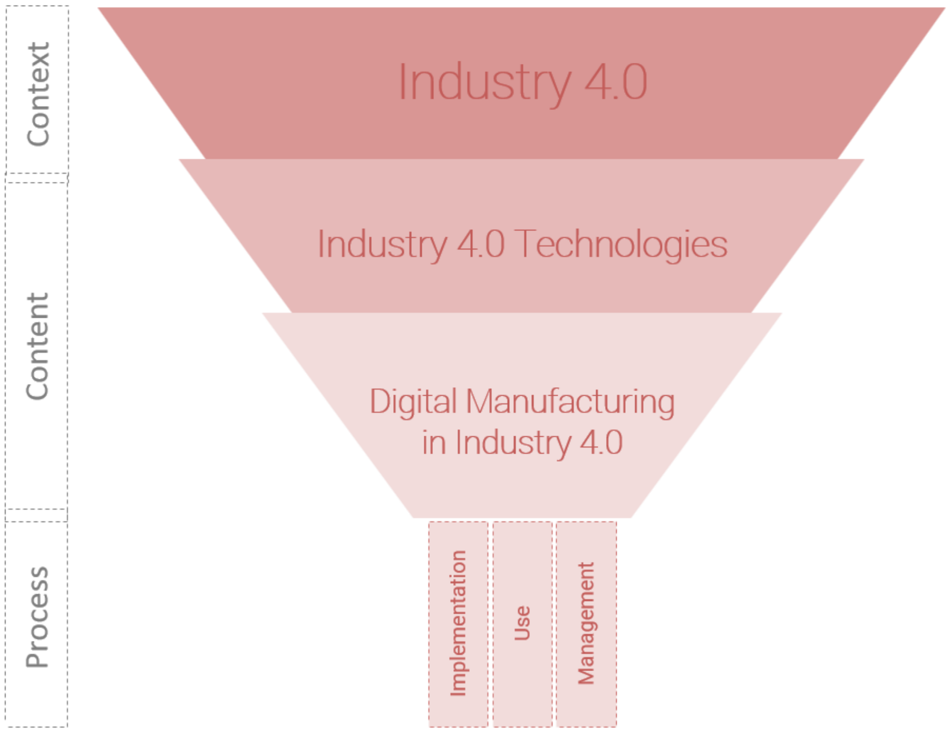
The chapter of findings and discussion present the main results of each phase of the research design. The mapping literature phase presents the bibliometric which helps to position the research and contribute to the understanding of the area. Also, the second step of literature review presents a review about the concept and application of DM in Industry 4.0 context and how the new technologies are influencing changes both for implementation and use. The content analysis presents the identification of the factors and the conceptual model. In the case study phase, a discussion of the factors and lessons learned through case studies within organizations indicate the how DM are being used to support the development of a production management model. The knowledge captured possibilities to use the critical success factors to guide the implementation and operationalize the use of DM according to the principles of Industry 4.0 and to the technologies related.

The last chapter presents the conclusion, including the research contributions, limitations, and recommendations for future research. The complete version of the papers indicated in Table 3 is presented in Appendix A.

2 THEORETICAL FOUNDATION

This chapter presents the main theoretical concepts that underlie this research. Some of these topics can be found in the papers, however, in order to facilitate standalone readability, a broader conceptual background is provided herein. Figure 2 presents a funnel view of theories and concepts.

Figure 2 - Theoretical foundation



Industry 4.0 represent the context of the current industrial revolution by which several aspects are changing, including many structural, technological and organizational factors. In this context, this research focuses on the technological content of advanced manufacturing technologies, also called Industry 4.0 technologies, mainly on Digital Manufacturing and how the other technologies are affecting it. In this content, we explore the implementation, use and management process of Digital Manufacturing in Industry 4.0. Next sections introduce the main concepts and important models and frameworks used to conduct the research.

2.1 Industry 4.0

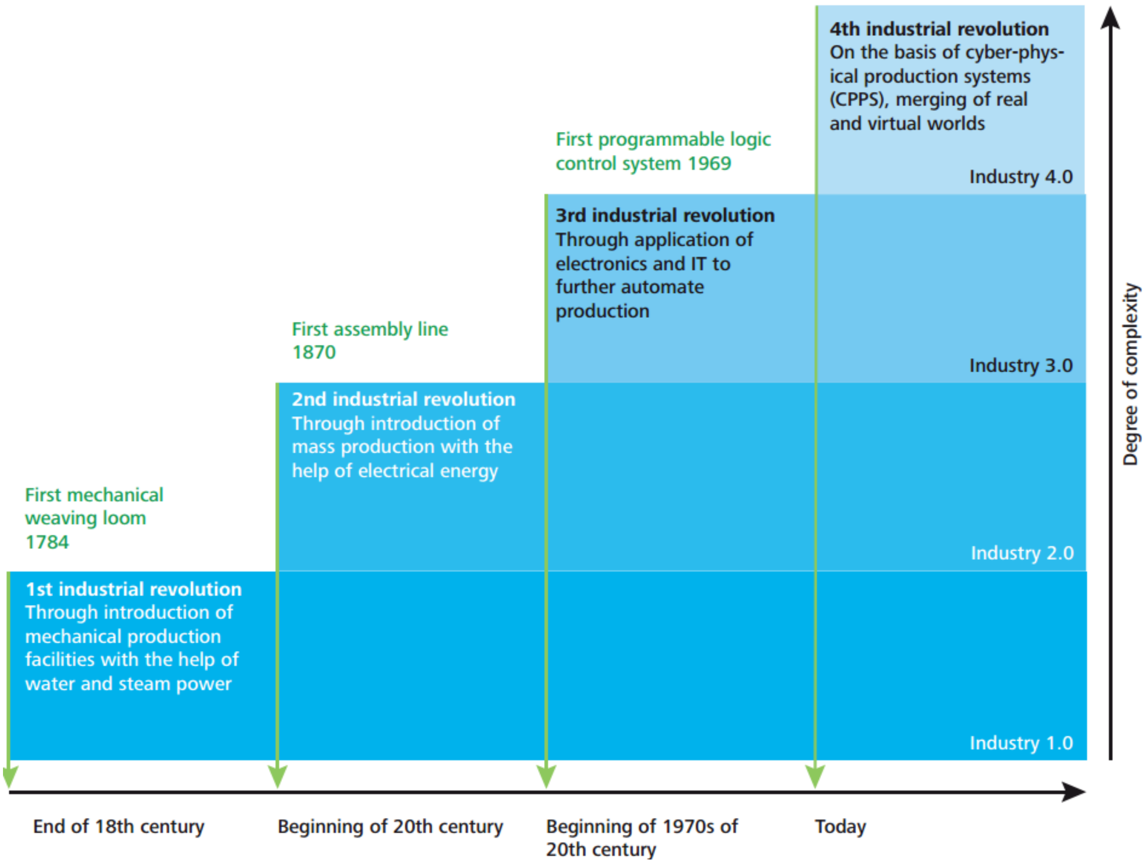
Industry 4.0 refers to the technological evolution from embedded systems to cyber-physical systems (CPS). Put simply, Industry 4.0 represents the coming of a fourth industrial revolution on the way to an Internet of Things, Data and Services. Decentralized intelligence helps create intelligent object networking and independent process management, with the interaction of the real and virtual worlds representing a crucial new aspect of the manufacturing and production process. Industry 4.0 represents a paradigm shift from "centralized" to "decentralized" production - made possible by technological advances which constitute a reversal of conventional production process logic. It means that industrial production machinery no longer simply "processes" the product, but that the product communicates with the machinery to tell it exactly what to do. It connects embedded system production technologies and smart production processes to pave the way to a new technological age which will radically transform industry and production value chains and business models (Sharma, 2018).

Terms including Industrial Internet (Bungart, 2014), Integrated Industry (Bürger & Tragl, 2014), Factory of the Future (Heynitz & Bremicker, 2016; Liao, Deschamps, de Freitas Rocha Loures, & Pierin Ramos, 2017), Smart Industry and Smart Manufacturing (Dais, 2014; Kusiak, 2017; Wiesmüller, 2014) are also used to address similar requirements and are subsumed by the concept of 'Industry 4.0'.

Guidelines for Industry 4.0 implementation are been strongly driven by governments, e.g.: Germany 'High Tech Strategy 2020' and 'Industry 4.0' (Kagermann, Wahlster, & Helbig, 2013); France – 'La Nouvelle France Industrielle' (Conseil National de L'industrie, 2016); United Kingdom – 'The Future of Manufacturing' (Foresight, 2013); United States – 'Advanced Manufacturing Partnership 2.0' (President's Council of Advisors on Science and Technology, 2014); European Comission – 'Factories of the future' and 'Horizon 2020' (European Commission, 2016); Japan – 'Super Smart Society' (Cabinet Office, 2015); Sweden – 'Smart Industry' and 'Produktion 2030' (Ministry of Enterprise and Innovation, 2016; Teknikföretagen, 2017).

What all these terms and concepts have in common is the recognition that traditional manufacturing and production methods are in the process of a digital transformation (see Figure 3).

Figure 3 - Definition of Industry 4.0



Source: DELOITTE, 2015

The core idea of Industry 4.0 is to use the emerging technologies in a way that business process and engineering process are deeply integrated making production operate in a flexible, efficient, and green way with constantly high quality and low cost (Wang, Wan, Li, & Zhang, 2016).

The following four main characteristics of Industry 4.0 demonstrate the huge capacity that industry and traditional manufacturing have for change (Deloitte, 2015):

1. **Vertical Networking**: of smart production systems, such as smart factories and smart products, and the networking of smart logistics, production and marketing and smart services, with a strong needs-oriented, individualized and customer-specific production operation.
2. **Horizontal Integration**: by means of a new generation of global value-creation networks, including integration of business partners and customers, and new business and cooperation models across countries and continents.

3. **Through-engineering**: throughout the entire value chain, taking in not only the production process but also the end product – that is, the entire product life cycle
4. **Acceleration through exponential technologies**: that, while not really new in terms of their development history, are only now capable of mass-market application as their cost and size have come down and their computing power has risen massively.

Have identified these four characteristics it is important to understand the individual technologies found within this that are presented next.

2.2 Industry 4.0 technologies

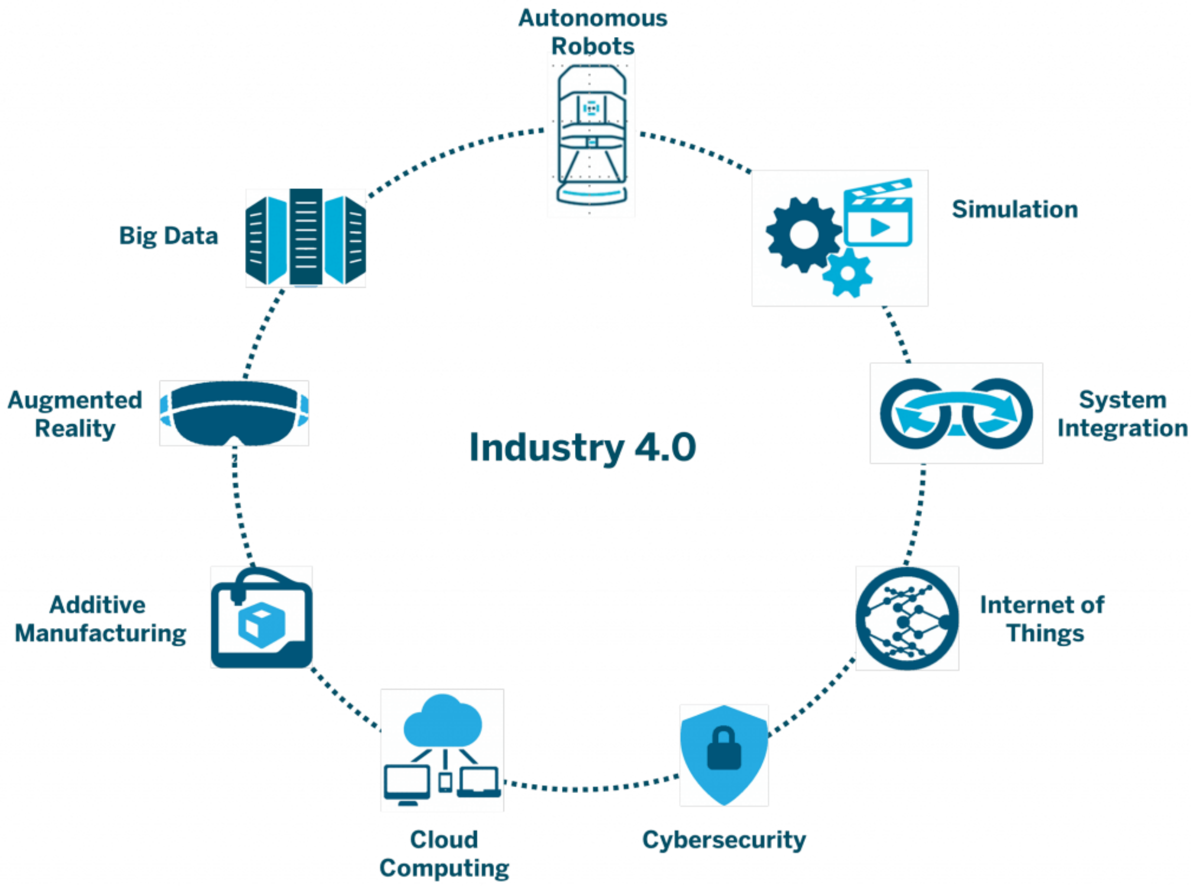
Before to go to Digital Manufacturing itself, it is needed to understand in broader way the advanced manufacturing technologies found in Industry 4.0. Industry 4.0 is a comprehensive transformation of the industrial production through the merging of technologies such as digital technology and the internet of things with conventional industry production systems (Davies, 2015). A variety of concepts and solution-components were drawn and studied to fulfill the vision of Industry 4.0, and these technologies have significant influence on manufacturing (Singh, Al-Mutawaly, & Wanyama, 2015; Sztipanovits et al., 2013). The technologies include Cyber-Physical Systems (CPS) as intelligent entities in production or manufacturing, Internet of Things as communication platform for CPSs, Cloud solutions for decentralized services, and Big Data solutions for high-performance processing of big data in manufacturing (Kagermann et al., 2013; Jay Lee, Lapira, Bagheri, & Kao, 2013; Sztipanovits et al., 2013).

Many 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 (Rüßmann et al., 2015).

Many models and frameworks (Baur & Wee, 2015; Bechtold, Kern, Lauenstein, & Bernhofer, 2014; Deloitte, 2015; Gartner, 2015; Griessbauer, Vedso, & Schrauf, 2016; Heynitz & Bremicker, 2016; Rüßmann et al., 2015; VDI, 2015) are presented trying to structure this new industrial paradigm. Most present not only technologies, but also structure dimensions, approaches, capabilities, and skills.

Early on, Boston Consulting Group developed an Industry 4.0 framework regarding only technologies, as presented in Figure 4 (Rüßmann et al., 2015). Seeking to understand the influence of Industry 4.0 technologies on digital manufacturing, we use this framework.

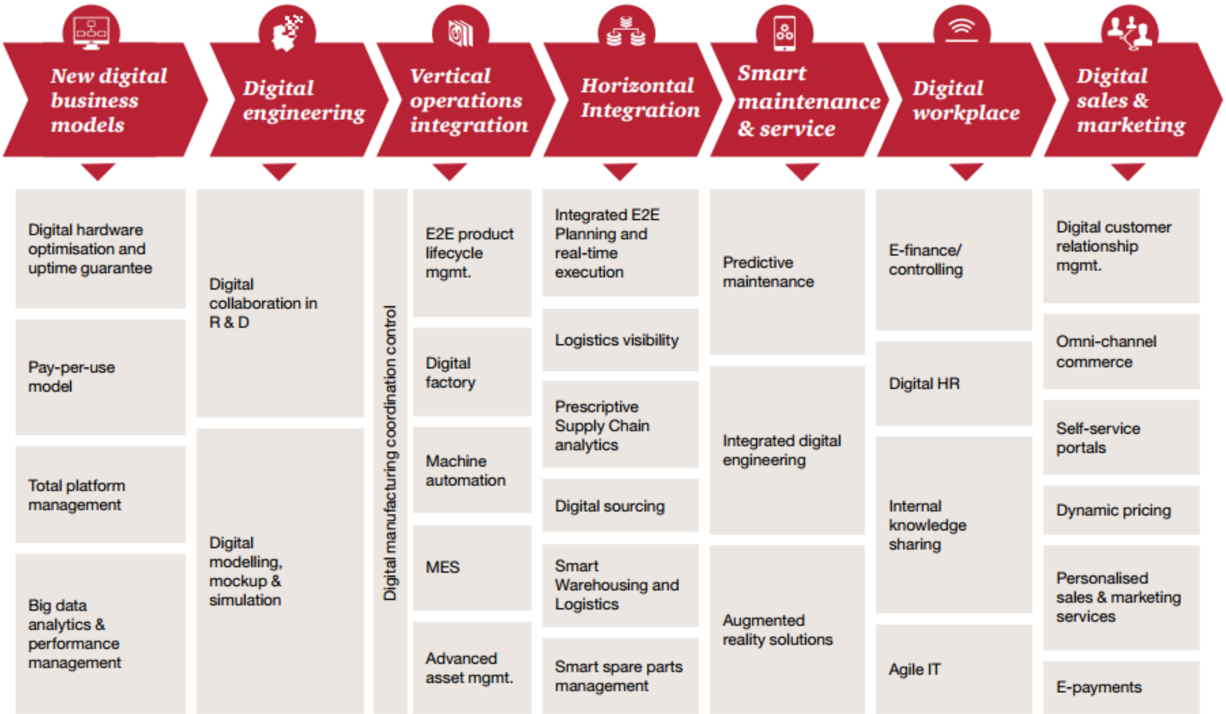
Figure 4 - Technologies in Industry 4.0



Source: RÜSSMAN et al., 2015

Although digital technology is expected to transform industries, there are a number of challenges and opportunities that need to be attended to better boost efforts. Figure 5 shows opportunities along the vertical and horizontal operational value chain and connect the role of digital manufacturing in the perspective of Industry 4.0. As can be seen in Figure 5, in a technology-based view, Digital Manufacturing is the technology used for vertical operations integration.

Figure 5 - Opportunities along the vertical and horizontal operational value chain



Source: PWC 2016

As explains Choi et al. (2015), Digital Manufacturing systems are responsible for data exchange and integration between heterogeneous software packages and systems, including legacy systems such as PLM, ERP, SCM, MES. These systems, by integrating other systems and enabling data exchanging, can play the role of vertical operations integration. Also, as seen in Figure 4, technologies enabling vertical and horizontal systems integration are one of the nine Industry 4.0 technologies. Digital manufacturing is one of the Industry 4.0 technologies playing the role of vertical systems integration.

Have point out the role of Digital Manufacturing in Industry 4.0, it is important to understand the origins of this technologies and how it is changing during the fourth industrial revolution, that are present next.

2.3 Origins of digital manufacturing

Digital Manufacturing has evolved from Computer Integrated Manufacturing (CIM), which was developed in the 1980s when the cost of computing went down to a level at which computers could be used extensively in manufacturing for machine and automation control, planning and scheduling (Coze, Kawski, Kulka, Sire, & Sottocasa, 2009).

According to Zhou and Chen (2012), during the 1980s, CIM naturally expanded to the field of robotics and artificial intelligence (AI). The conception of CIM has functioned as a connection between manufacturing, systematic science, and other related issues, and they are merging into the manufacturing industry. The CIM age, which takes Harrington, Merchant and Bjorke as representative, includes the physical process of each manufacturing technology, control issues, as well as the scheduling of Flexible Manufacturing Systems (FMS). Its structural scheduling connects the original CIM concept with related scientific issues, developing manufacturing from engineering to manufacturing science. The combination of organizational sciences such as Total Quality Management (TQM), Just in Time (JIT) manufacturing, Concurrent Engineering (CE), and Lean Production (LP), with engineering science is represented by CIM.

The new concept of open structural manufacturing and agile manufacturing runs through the 1990s. Rapid reconfigurable enterprises should make reactions to new consumers that have requirements on ‘‘due date, quality and product variety’’. Total quality management is thus added as a new outer concept circle to the CIM circle, known as CIM++, which includes CE (totally quality management), enterprise integration (virtual corporations) and customer needs. In the newly added circles, CE is a topic that is closely related to TQM (Zhou et al., 2012)

Zhou and Chen (2012) comment that by the late 1980s the organizational sciences of TQM, JIT, CE and LM, combined with the engineering sciences of CIM, and all began to create an important improvement in U.S. manufacturing. This set the stage for the economic growth of the 1990s. In sum, from the evolution process above, CIM will adopt the organizational science issues. In the middle of 1990s, manufacturing based on the Internet became an extension of the above new trends, emphasizing on shared design and manufacturing services.

With the rapid development of modern science and technology, especially the quick development of microelectronics, computer technology, network technology and information technology, the face and meaning of manufacturing theory, manufacturing technology, manufacturing industry and manufacturing science lead to a fundamental and revolutionary change. Manufacturing must have high-quality management and operation. Human factors, cooperation and competition across enterprises, collaboration and the integration of manufacturing resources are not only a technical problem. Technology Management is the basis of those manufacturing issues. Apparently, the trend of manufacturing becoming increasingly multidisciplinary is inevitable. With the development and progress of manufacturing science and technology, more and more subject knowledge will be used in future manufacturing fields, forming the new basis of manufacturing science. Based on the characteristics above, manufacturing has developed as a multidisciplinary integrated system, and thus as a manufacturing science. New engineering science technologies, such as the Web, offer new ways of creating products and services. However, due to more and more digitized forms and knowledge representation of manufacturing activities and manufacturing information, the manufacturing process and manufacturing management calls for a fresher and larger outlook than the old ways. Digital Manufacturing (DM) has quietly entered our lives (Zhou et al., 2012).

2.4 Digital Manufacturing implementation and use in industry 4.0

In 2005 Dalton-Taggart (2005) stated that “the recent technology improvements are making digital manufacturing real to many, and many companies are using pieces of digital manufacturing without realizing it”. This remains true. And as cited by Coffey (2015), when asked for a group of manufacturing people to describe what digital manufacturing is and how it works, they are all likely to emphasize different areas based on their experience and specific job responsibilities.

Digital manufacturing is a whole range of technologies that have been evolving over decades, and each one begins with a different starting point. For the most part, all the different capabilities contained under this umbrella were developed in silos and only recently have manufacturers realized the benefits of connecting and integrating the different parts. But the significant technology evolution in the last few years have had a similar effect on digital manufacturing.

Several technologies that support digital manufacturing are quite well established and mature used by many organizations. However, their combined and integrated use, as well as the possibility of real-time application, is transformative, creating many new possibilities for industry application. That is primarily due to digital manufacturing not being a philosophy but a methodology that integrates technologies and company departments focusing on better performance of the product lifecycle. For this reason, the technology evolution disposes digital manufacturing to change its characteristics.

Most of the definitions found in the early years cover only modeling, digitization and information management (Butterfield et al., 2007; Curran et al., 2007; Mahesh, Ong, Nee, Fuh, & Zhang, 2007; Maropoulos, 2003). In recent years, definitions are broader with inclusion of responsibilities regarding decision making, citing the potential for more collaborative environments and interoperability (benefits also sought by the inclusion of industry 4.0 technologies). Digital Manufacturing is concerned with the representation of the product and the process in a digital way, but also 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 role of Digital Manufacturing (MESA, 2016).

Although DM already is in use, there have recently been several technical changes and their application domain in production. This is mainly driven by the new industrial context and the rise of advanced manufacturing technologies. These changes led the European Commission (EFFRA, 2016) to position DM as one of the five key priorities for the FoF 2020 - Factories of the Future - the strategic proposal presented under the Horizon 2020. This seeks to encourage some implementation initiatives in synergy with the ongoing waves of Industry 4.0. According to them, DM enables the provision of services that support manufacturing in a broad sense. These services are associated with collecting, storing, processing and delivering data. These data are either describing the manufactured products or are related to the manufacturing processes and assets that make manufacturing happen (material, machine, enterprises, value networks and factory workers).

According to Siemens (2018) and Dassault (2018), developers of tools for digital manufacturing, Design-centered DM has functions for support design and engineering tasks; Production-centered DM supports manufacturing preparation tasks; and Control-centered DM focuses on monitoring and controlling by direct interface with production systems and machines on the shop floor. The framework’s applications within the domains are recent, more integrated and allow the delivery of greater value, but still within the logic of the model.

3 RESEARCH DESIGN

The purpose of this chapter is to define how the research will be formulated, to establish methods, strategies and research tools that will allow the achievement of the objectives established for this thesis, using principles of scientific methodology. Thus, the research strategy, the stages of the research, and the instruments and techniques for data processing will be defined. The proposed methodology considers literature review, survey, field research, case studies and development of orientation models.

This research is composed of 4 parts, which despite being treated sequentially and together provide a consistent result, each part presents independent research strategies and their results can also be consumed independently. Therefore, research strategies will be presented independently.

According to Vergara (2007), scientific research is a science activity that provides access to knowledge in a consistent, coherent, logical and is well accepted by the scientific community. According to the author, scientific research can be classified in two ways: "as to the ends" and "as to the means". Table 4 presents in a structured way the research strategy regarding the ends and the means of each of the research stages.

Table 4 - Research Strategy

Stage	Focus	As to the ends	As to the means
1	Mapping literature	Exploratory	Bibliographical
2	Content analysis of DM in Industry 4.0	Exploratory and Descriptive	Bibliographical
3	CSF for implementation and use of DM in Industry 4.0	Explanatory	Bibliographical, documentary, field research and survey
4	Development of the framework for implementation and use of DM in Industry 4.0	Exploratory, Applied, and Methodological	Research-action and Case study

According to Vergara (2007), the research strategies can be described as follows:

1) As to the ends:
   - Exploratory Research: it is carried out in an area in which there is little knowledge accumulated and systematized. By its nature of probing, it does not contain hypotheses that, however, may arise during or at the end of the research;
   - Descriptive Research: It exposes characteristics of a certain population or given phenomenon. It can also establish correlations between variables and define their nature.
   - Explanatory Research: Its main objective is to make something intelligible. Justify its reasons. It aims, therefore, to clarify which factors contribute in some way to the occurrence of a certain phenomenon.
   - Methodological research: it is the study that refers to instruments of reality capture or manipulation. It is, therefore, associated with ways, forms, methods, procedures to achieve an end.
   - Applied Research: it is fundamentally motivated by the need to solve concrete problems. It has a practical purpose and it is mainly situated at the level of speculation.

2) As to the means:
   - Bibliographic research: it is the systematic study developed based on material published in books, magazines, newspapers, electronic networks, that is, material accessible to the general public. It provides analytical tools for any other type of research, but it can also run out on its own. The published material may be primary or secondary source;
   - Documentary Research: it is carried out on documents kept inside public and private bodies of any nature;
   - Field research: it is an empirical investigation carried out where a phenomenon occurs or occurred or that has elements to explain it. It may include interviews, questionnaire application, quizzes and participant or non-participant observation;

- Survey: a sociological investigation that uses question based or statistical surveys to collect information about how people think or act about a related topic.
- Case Study: it is the circumscribed to one or a few units. It has depth and detail character. It may or may not be carried out in the field.

Have point out research strategies chosen to conduct this research, the methods used to operationalize those strategies are described next.

3.1 Mapping literature

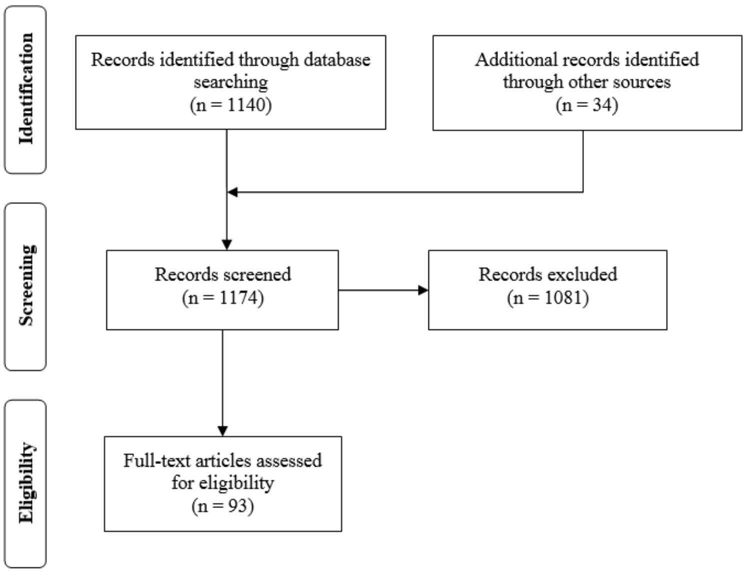
This section details the steps related to the SLR and bibliometrics techniques applied. It is important to note this process constitutes the first phase of research and the meaning of each term, its scope, purpose, and emphasis was still unclear. Results from these phases are used both for solve this problem and for bibliometrics purposes.

3.1.1 Systematic literature review

This step a systematic literature review (SLR) is conducted to explore the literature on digital manufacturing. In the first step, the method of SLR was applied to map the body of knowledge of this field and to generate significant information about the theme. Despite the importance of the literature review for research in general, scholars notice that some reviews in the management field are more narrative and subjective, and because of this, the SLR begins to be used offering a transparent and replicable process that considers all relevant studies identified through a rigorous protocol (Andreini & Bettinelli, 2017; Tranfield, Denyer, & Smart, 2003). In this sense, a SLR is carried out to identify studies addressed on the theme.

The search terms selected to use are ‘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 (1961) 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 (Sayers, 2007). Figure 6 illustrates the search strategy using the PRISMA diagram flow (Moher, Liberati, Tetzlaff, & Altman, 2009).

Figure 6 - Search strategy and studies selection (PRISMA flow diagram)



Problem definition

The central questions that guide the SLR, in the problem definition stage, are "what differs 'digital manufacturing' from 'digital factory'?" and "what the scope of application of Digital Manufacturing is?". An extension of scope is addressed in a later phase when concepts 'smart factory' and 'smart manufacturing' are also included in the analysis but were not considered in this stage of the project.

Scoping study definition

The search terms were established by iterative testing on the platforms Springer, IEEE, Science Direct and Emerald. Due to the limited number of studies found no Boolean operator for limiting (or) are used. The terms used are only: digital manufacturing and digital factory.

Search strategy definition

The search strategy encompassed the consideration of papers in English published until 2015 and referenced in the following platforms: Springer, IEEE, Science Direct and Emerald. The first search attempt was made in the database considering the terms in all fields, but it resulted in 1140 results, which is beyond the scope of the authors' analysis. Thus, a new attempt was made limiting the results only to articles whose terms appear in the title or keywords. The overall search in these databases resulted in 112 papers.

Exclusion criteria application

The exclusion criteria application step resulted in removing: (a) papers duplicated since some of them appears in more than one platform or use both terms resulting in more than one appearance in some platforms; (b) references without available full-text; (c) editorials documents for journal issues.

Data analysis

A total of 93 papers were selected and composed the final portfolio of papers. Data such as the publication year, the authors and their countries, research department, keywords, publication journal, among other data are analyzed.

3.1.2 Bibliometric and keyword analysis

Bibliometric analysis was applied to describe current research topics related to the theme. As suggested by Lacerda et al. (2012), the bibliometric analysis concept is based on the quantitative evaluation of certain parameters for a defined set of articles, such as their authors, references, citations, and journals. The bibliometric analysis seeks to identify what was produced by the scientific community on a specific research area and to evaluate main trends. In order to achieve them, bibliometric techniques are used to describe current research themes through a quantitative approach.

3.2 Content analysis

This section details the steps related to the content analysis. It is important to note the purpose of this method still constitutes the first phase looking to clarify the differences between terms ‘digital manufacturing’ and ‘digital factory’ and make it clear based on a systematic approach.

Search strategy

To analyze what are the main characteristics of each term, the set of papers was analyzed based on the different definition proposed by the authors for both terms. For this, the set of pre-selected papers was submitted to a filter following some steps: (i) there are author's own definition for ‘digital manufacturing’ or ‘digital factory’; or (ii) there are definition and concepts cited and/or adopted by the papers’ authors, related to ‘digital manufacturing’ or ‘digital factory’, which are traceable to their sources. The select papers are added to the systematic literature review portfolio, and their references are scrutinized for tracing DM concepts. It is called snowballing technique.

Snowballing technique

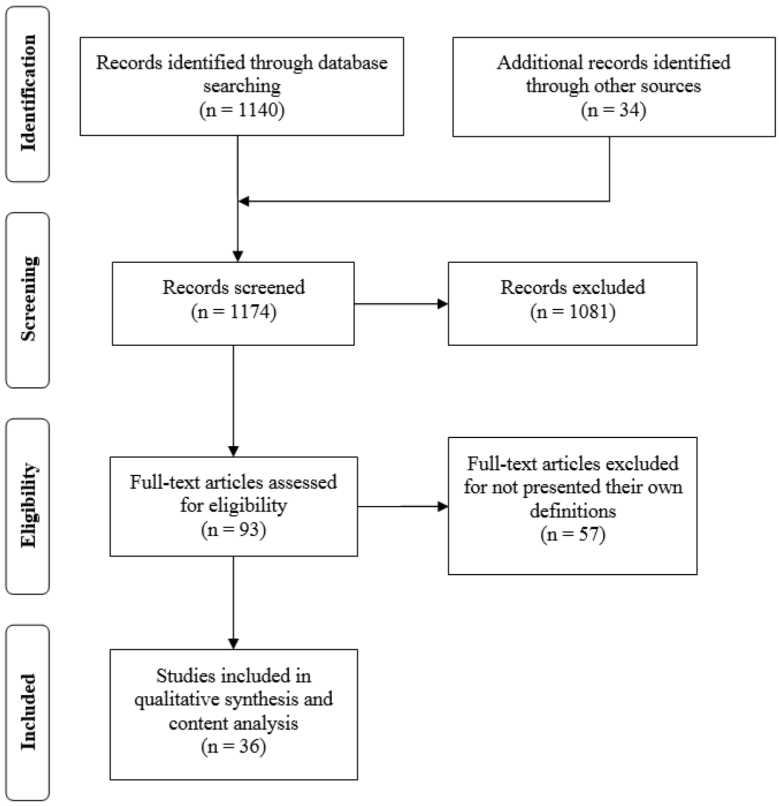
This snowballing technique, that is similar to snowball sampling (Goodman, 1961) in sociology research, is typically used to recover cited references. It consists of searching papers listed in references of select papers, thereby growing the sample. The new papers should fulfill the previously set criterion to be added to the portfolio. The search cycle ends when there is no repetition of references or the absence of new references (Sayers, 2007). At the end, the portfolio is formed by original contributions for conceptualizing ‘digital manufacturing’.

Data selection

The first phase selected among the 93 papers those that presented their own definitions: 20 of them met the criteria and were directly included in the portfolio. The second phase consisted to apply the snowball technique to the 93 papers. This process resulted in 34 new papers to be analyzed. From these, 16 of them presented their own definitions and also were included in the portfolio. Thus, the portfolio used for the literature review and content analyze in this research contains a total of 36 papers (See Figure 7).

From these 36 papers, original definitions for 'digital manufacturing' were found in 13 papers and for 'digital factory' were found in 23 papers. Terms that primarily define characteristics or function are compiled. Some terms used to define terms were clustered for analytical purposes when contextually present similar meanings (e.g. simulation, simulations, simulated, simulate).

Figure 7 - Selection of original contributions



Data analysis

The selected papers are studied through the lens of content analysis to compile the identified concepts. This type of analysis is defined as a set of 'communication' analysis techniques that uses systematic procedures and objectives to describe the content of 'messages', allowing the inference of knowledge regarding the variables identified in these 'messages'. The communication process is understood through a community of academics and practitioners, whose work is related to a certain research topic. 'Messages' are the pieces of text that form the papers' manuscripts (Bardin, 2011).

Therefore, techniques described by Bardin (2011) were used. Based on Bardin's perspective, content analysis consists of three chronological steps: (i) pre-analysis; (ii) the exploitation of the material; (iii) treatment of results, inference and interpretation.

Pre-analysis consists the phase of organization, in which the objective is to operationalize and systematize the initial ideas. The second step, the exploitation of the material, consists of the definition of the categories and the codification. Coding the material selected for the analysis consists of a transformation of the raw data of the text which allows a representation of the content to be reached (Bardin, 2011). Considering the author's perspective, categorization is defined as an "operation of classifying constituent elements of a set, by differentiation and, subsequently, by gender grouping, with the previously defined criteria." The categories group is a set of elements with characteristics in common under a generic title. The treatment of the results obtained, the inference and the interpretation can be treated based on statistical operations. Inferences and interpretations are made based on the significant and faithful results obtained. The software Atlas TI® was used to assist the second and third stage of this analysis.

3.3 Critical success factors for DM implementation and use in Industry 4.0

This section details the second phase of this research aimed to develop a theoretical-practical framework for DM implementation and use in Industry 4.0. Thus, several steps and a multi-method approach are used, that includes content analysis, preliminary case study (or pilot case) in a large automotive company and a survey conducted with 113 specialists in DM and Industry 4.0, including researchers, users, managers and consultants. The factors were identified and studied, for each factor a categorization is proposed, and a conceptual model is introduced.

3.3.1 Content analysis

To map out the critical success factors for digital manufacturing implementation and use in Industry 4.0 a content analysis on the selected papers were carried out. However, since only a few papers address discussions about digital manufacturing implementation and none of them in an Industry 4.0 context, it was added technical reports of specialized consultancies working on Industry 4.0 to obtain updated and contextualized information.

3.3.2 Pilot case

Company selection

The pilot case was performed in one of the largest multinational automotive companies, which has a digital transformation purpose adopting many Industry 4.0 technologies to solve problems and to address new opportunities. This company has been conducting the DM implementation process for two years. These interviews aim to map the main organization difficulties during this process and to verify which CSF were not well developed, as well identify new variables that directly affect the success of implementation project.

Procedure

Interviews were held to map the organizational difficulties during the implementation process and to identify which factors were not well developed, as well as identify any additional variables that directly affect the success of implementation project. twelve interviews were carried out with employees from several different departments, involving: product and process engineering, layout development, equipment development and IT. Several departments were consulted enabling a global view of the company situation in relation to digital manufacturing.

Quality control

Unstructured interviews were used in this phase to obtain the lowest level of anchoring (Kahneman, 2013), thereby enabling the test whether or not the responses of staff dealing with the implementation process in practice correspond to what is identified in the body of theory work.

3.3.3 Survey

Having mitigated the anchoring problem in the first phase, a survey was select for the second technical factor refinement. The survey was applied to professionals working with digital manufacturing. The survey is more comprehensive than the pilot case, since it incorporates a greater variety of respondents, such as users, managers, implementers and researchers on digital manufacturing and Industry 4.0 from several countries, enterprises, and research institutes. This has the benefit of supporting the capture of the broader organizational changes related to technological change.

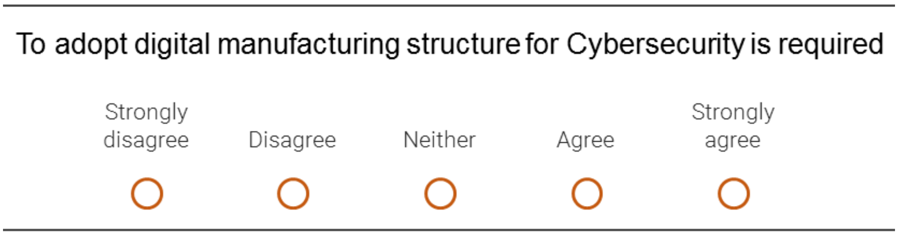
Preliminary survey

A preliminary survey was carried out to ensure the data collection was applicable in a real-world scenario. The test was conducted with people from three key groups: (i) users from industry that use various DM tools on a daily basis, (ii) consultants who assist on a DM implementation process, and (iii) researches exploring DM use. Note that those that responded to the preliminary survey were not allowed to participate in the conclusive survey, as this could disqualify the sample.

Survey content

The questionnaire contained 31 questions and was divided into the following five blocks: (1) sample characterization; (2) questions related to technical aspects; (3) questions related to organizational aspects; (4) question related to project management; (5) questions related to external aspects. Likert scales were used since it is a relatively reliable way to measure opinions, perceptions, and behaviors. Figure 8 shows an example of question and scale presented to respondents.

Figure 8 - Sample question and scale



Selection of respondents

The survey focused in qualified professionals working with digital manufacturing in three main activities (i) users and managers from industry that use and manage various DM tools on a daily basis, (ii) consultants who assist on DM implementation process, and (iii) researches exploring DM use. Some guidelines for selecting respondents were used to mitigate quality risks.

The selection of respondents to compose the group of researchers was done mainly through the ResearchGate platform. It was selected only users who had already published original papers related to digital manufacturing or Industry 4.0. 600 invitations to participate in the survey were sent through this strategy.

Reaching industrial respondents, a selection of users was performed through LinkedIn. Within a specific group of Digital Manufacturing on LinkedIn, users who presented in the experience description activities directly related to the use of digital manufacturing tools in a daily basis, and/or managers of departments running under DM system were primarily contacted. 180 invitations to participate in the survey were sent through this strategy.

Reaching consultants respondents, the same strategy used to reach industrial respondents was performed. However, due to the low rate of responses in this group while the survey was conducted, it was also necessary include into the strategy telephone and email contact. Contacts were obtained by indication from professionals in the area. 20 invitations to participate in the survey were sent through this strategy.

In total, 800 invitations to respond the survey were sent.

Operationalization

LinkedIn and ResearchGate platforms were used to select qualified respondents. Qualtrics software was used to operationalize the survey. For calculations, it was used Statistical Package for Social Sciences software (IBM/SPSS).

Quality control

Only questionnaires that contained answers to all questions were considered as valid. Forms with one or more unanswered questions were discarded.

Data analysis

The collected data was initially tested for index stability using Cronbach Alpha coefficient (Hair, Black, Babin, & Anderson, 2009). Cronbach's alpha does not simply measure test homogeneity or unidimensionality as test reliability is a function of test length. A longer test increases the reliability of a test regardless of whether the test is homogenous or not (Cronbach, 1951). As a rule of thumb, if $\alpha \geq 0.7$ then the answers are considered reliable in research involving human responses (Carlbring et al., 2007). A much higher value of alpha (>0.90) suggests redundancies and that the test length should be shortened since there is item redundancy (Tavakol & Dennick, 2011). It is recommended to have an alpha score between 0.70 and 0.90 (Streiner, 2003).

The cut-off points were defined based on the global average of concordance and discordance on the items. Factors that present average above the superior cut-off point or below the inferior cut-off point were analyzed. Factors within the cut-off points limits were kept as CSF.

Questionnaire validation

A reliability test was performed to ensure the information obtained was valid, this resulted in a Cronbach's alpha of 0.850. To corroborate with the results and to ensure that the sample size was not contributing to a biased alpha value, the same test was applied within the four constructs of the factors list: technical, organizational, project management and extern. The alpha values for the constructs were 0.862, 0.785, 0.692 and 0.750, respectively. With these results it is possible to admit the data as adequate to obtain information and to be used for the purpose for which it was collected.

Sample composition

A total of 113 completed surveys were received. Table 5 presents the sample composition of respondents based on their main professional activities. It is noted that approximately 21% of the respondents come from the industry, 68% are researchers working on DM in this field, and 10% of the respondents are consultant dealing directly with the implementation process.

Table 5 - Main professional activity of respondents

Professional Activities	**Frequency**	**Percent**
Industry	23	21,3%
Consulting	11	10,2%
University or R&D centre	78	67,6%
Other	1	0,9%
Total	**113**	**100%**

For sample characterization, respondents were asked about their knowledge on digital manufacturing technologies. Table 6 summarizes the responses by respective professional activity.

Table 6 - Sample characterization by knowledge and professional activity

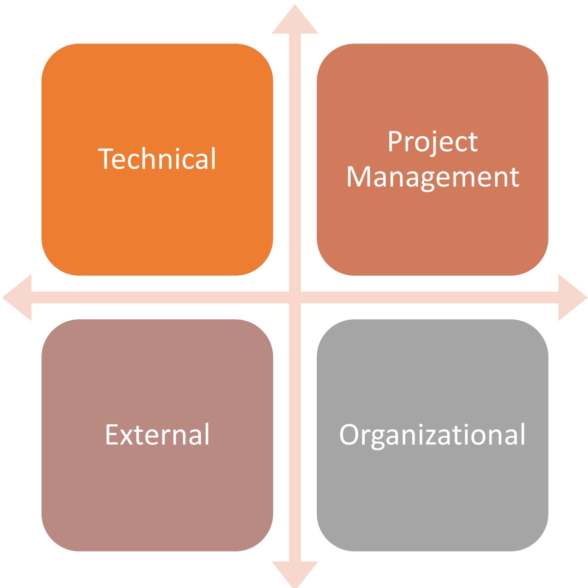
Professional Activities	**Novice**	**Advanced Beginning**	**Intermediate**	**Competent**	**Expert**
Industry	-	1	8	9	5
Consulting	-	-	3	4	4
University or R&D centre	2	4	13	41	18
Other	-	-	-	1	-
Total	**2**	**5**	**24**	**55**	**27**

More than 70% of the respondents answered that they have high knowledge (competent or expert) in the subject. Only 6% declared themselves novices or advanced beginners.

3.4 Framework development

Factors were categorized in 4 dimensions based on Risk Breakdown Structure proposed by PMI (2008): (i) Technical: includes aspects such as technical, technology, complexity and interfaces, performance and quality; (ii) Organizational: includes aspects such as estimates, planning, control and communication; (iii) Project management: includes aspects such as project dependencies, resources, financing and prioritization; (iv) External: includes aspects such as subcontractors and suppliers, regulations, market and customer. Figure 9 shows the 4 categories used.

Figure 9 - Factors categories



The framework is composed by the selected factors and are divided in six phases, an adaptation of the PPDIOO methodology for DM systems. The six phases are: Prepare, Plan, Design, Implement, Operate, and Optimize (see Figure 10).

Figure 10 - PPDIOO methodology

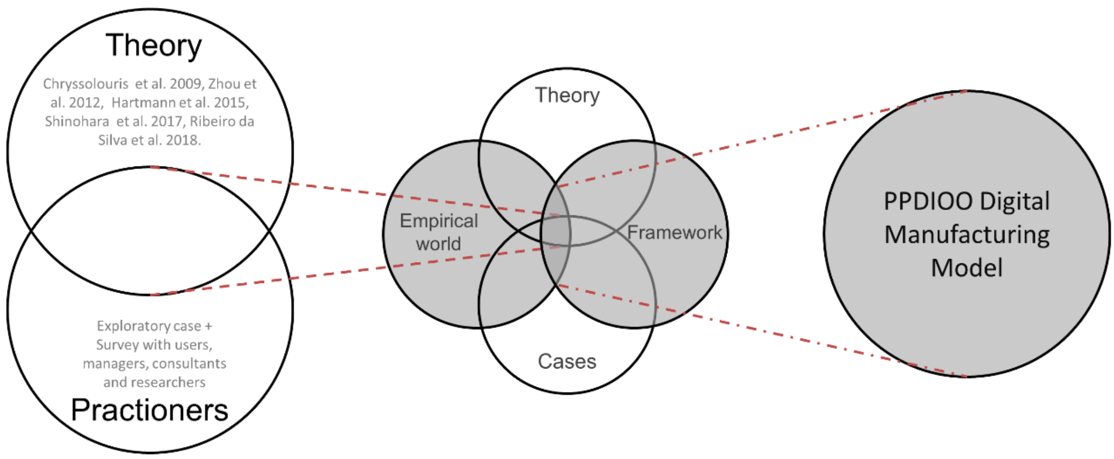
Thus, for the development of the model that guides implementation and use of DM in Industry 4.0, factors are analyzed into the four proposed categories, along the PPDIOO meta-framework, and through the lens of the models proposed by Morton & Rockart (1984) that aims to analyze the implications of IT changes in the organizational strategy and the model proposed by Linton (Linton, 2002) which aims to structure the variables which influence on the technological implementation process.

3.5 Case studies

A case study approach was chosen to identify and review what is the role of digital manufacturing in Industry 4.0. Case studies also to discuss how companies addressed the identified critical success factors for DM implementation and use and how they are using Industry 4.0 technologies to improve the usage of DM tools in this new industrial context.

A research strategy that encompasses case studies in different sectors and companies at different stages of digital manufacturing adoption has been chosen for an instrumentalization of the factors can be guided by the findings in the empirical world. Key aspects of the methodology used in this research are shown in Figure 11.

Figure 11 - Research strategy for case study



Defining case study scope

Selected organizations (or a national site from a multinational organization) should be implementing or using digital manufacturing. There is no restriction based on location, sector, or organizational size.

Questionnaire development

A questionnaire with 15 questions was developed covering the 6 phases for adopting digital manufacturing supporting the understanding about the factors covered and how to conduct each phase in an Industry 4.0 context. Table 7 presents the list of questions applied in the case study.

Table 7 - Questionnaire for case studies

Categories	Questions
Context	Are the organization adopting Industry 4.0 technologies, such as IoT, VR/AR, autonomous robots, among others?
	How long have the company been using digital manufacturing system?
	Which digital manufacturing system is used? (Delmia, Tecnomatix, etc.)
Prepare	Is digital manufacturing really necessary for the company? What are the characteristics that make it needed?
	Despite the costs of implementing and maintaining the systems, is it feasible to have digital

	manufacturing implemented?
	Was the top management committed with digital manufacturing systems adoption?
Plan	Was there a team focused on the selection, implementation and integration of Industry 4.0 technologies?
Design	Which other systems are integrated to digital manufacturing system? (ERP, MES, CRM, PLM, etc)
	Are the data used for the projects real time data? How are they collected (IoT)?
	Is the factory floor connected to digital manufacturing system?
	Are the company digitally integrated to their suppliers by DM systems? ⁄ If yes: how is this integration designed and implemented? ⁄ If no: why?
Implement	When the company started using digital manufacturing, did it changed how people used to work?
	Considering all information is digital, connected and integrated into one platform, how does the company handle the risks and ensures the safety of the operation?
Operate	How does work training in digital manufacturing tools for the employees?
Optimize	How does the company respond to new market developments? ⁄ Does the company seek opportunities to adopt new technologies OR adopt those technologies that solve problems related to the strategy? (e.g. blockchain)

Defining sources of evidence for data collection

For each participating organization, one or more individual interviews were conducted with users of digital manufacturing tools or managers responsible for units running under digital manufacturing systems. Besides that, protocol collects evidences from documents, records, and observation to ensure the validity of the data.

Sample overview

According to Barratt (2011), multiple cases can augment external validity and help guard against observer bias. A sample of six companies were selected, representing companies of different sizes, complexity, sectors and DM tools used. Three of them from the automotive sector, two of them from technology sector, and the last of from Aerospace and Defense sector.

In some cases, several people had to be interviewed for all question to be answered, since individuals lacked the necessary information to answer all questions. In other instances, one interviewee possessed enough comprehensive information to suffice. Table 8 presents an overview of the organizations and people interviewed.

Table 8 - Sample overview

Organization	Sector	Job positions interviewed
Company 1	Aerospace & Defense	3 positions - Head of Technical Discipline - Manager of Manufacturing - Coordinator of IT systems for production
Company 2	Technology	1 position - Digital Manufacturing Engineer
Company 3	Automotive	2 positions - Digital Manufacturing User - External consultant of Digital Manufacturing
Company 4	Automotive	2 positions - Digital Manufacturing User - Researcher of Digital Manufacturing
Company 5	Technology	1 position - Manufacturing Engineer for Digital Manufacturing
Company 6	Automotive	1 position - Innovation Project Leader

Operationalization

Interviews with representatives from companies three and six were conducted in person, while the other interviews were conducted online using the software Skype for Business. In addition to the interviewer taking notes throughout the interviews, all the interviews were recorded for later consultation as needed. Since not all interviews were conducted in English, some citations in Paper 5 have been translated

Company analysis

During the actual interviews, to capture how each organization use DM tools and how it is aligned to Industry 4.0, a brief initial characterization was conducted. Table 9 presents the

DM system used for each organization, length of use, integration with suppliers and with legacy systems, capture and use of real time data, as well as if the technology adoption is reactive or proactive solving problems and exploring new opportunities. Taken together it provides an understanding of how each organization employed and evolved in using DM.

Table 9 - Companies characterization

Companies	DM System	Period since implementation	Integration with suppliers	Legacy systems integrated	Real time data	Technology adoption	
						Reactive	Proactive
Company 1	Delmia	10 years	○	○	○	●	○
Company 2	Tecnomatix	5 years	●	●	●	○	●
Company 3	Tecnomatix	4 years	●	◑	○	○	●
Company 4	Delmia	3 years	○	○	○	◑	◑
Company 5	Tecnomatix	7 years	◑	○	○	●	○
Company 6	Delmia	3 years	○	○	○	◑	◑

Data analysis

All answers were analyzed, triangulated and summarized seeking to identify similarities and differences, as well as drivers and barriers at each stage of the process. After all answers summarized a discussion correlating these findings to literature review are presented.

4 FINDINGS AND DISCUSSIONS

This chapter presents the findings and discuss the results organized by ‘mapping literature’, ‘content analysis’, ‘technology integration’, ‘critical success factors’, ‘digital manufacturing framework’ and ‘case studies’.

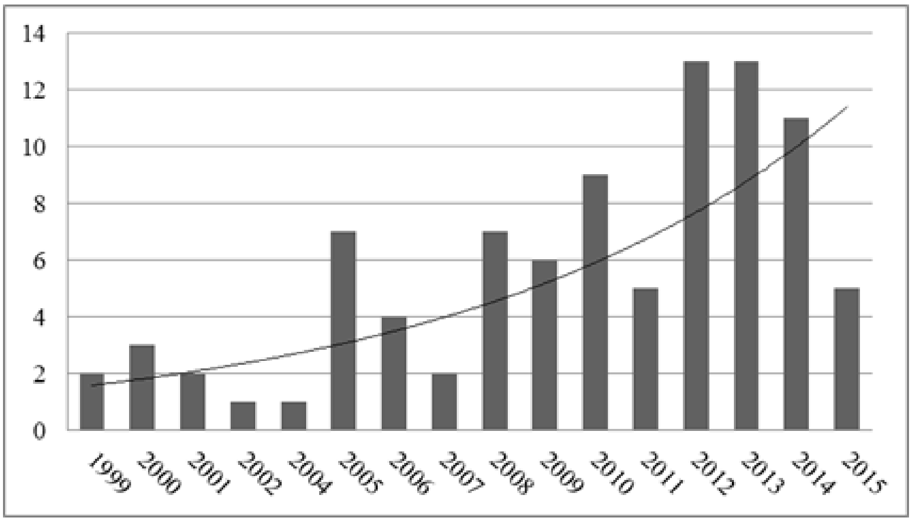
4.1 Mapping literature

The first section presents the results of the bibliometric and keywords network analysis performed with the SLR outputs. Through the analysis of the compiled data, five aspects of publications related to digital manufacturing were identified: (i) the evolution of publications (Figure 12); (ii) the main journals and conferences (Table 10); (iii) the areas and departments that are studying digital manufacturing (Table 11); (iv) the countries that publish the most about digital manufacturing (Figure 13); (v) terms related to digital manufacturing (Figure 14).

It is worth mentioning that the authors of the publications were also studied, however, no author presented three or more articles. Thus, there is a diversity of authors approaching digital manufacture. In addition, a significant concentration of articles was observed in the Science Direct and IEEE databases, with a total of 84% of all articles collected.

Considering the bases used for developing this study, the first articles related to digital manufacturing was published in 1999. Although there are variations in the amount of publications over the years, an increasing tendency is identified. Figure 12 shows an overview of publications since 1999 until 2015.

Figure 12 – Papers published related to digital manufacturing



The set of articles selected has different approaches to digital manufacturing, such as conceptual models, comparison of conventional engineering and digital manufacturing and case studies. The most significant journals and conferences in the context of digital manufacturing are cited in Table 10.

Table 10 - Publication by journals/conferences between 1999-2015

Journal/Conference	**Frequency (%)**
Procedia CIRP	13,2%
Computers in Industry	5,5%
Winter Simulation Conference	4,4%
Procedia Engineering	4,4%
CIRP Annals - Manufacturing Technology	4,4%
The International Journal of Advanced Manufacturing Technology	3,3%
The International Journal on Interactive Design and Manufacturing	3,3%
Others	=< 3%

Digital manufacturing is a subject of study in different departments, especially in Industrial Engineering and Mechanical Engineering, as can be seen in Table 11.

Table 11 - Publication by departments between 1999-2015

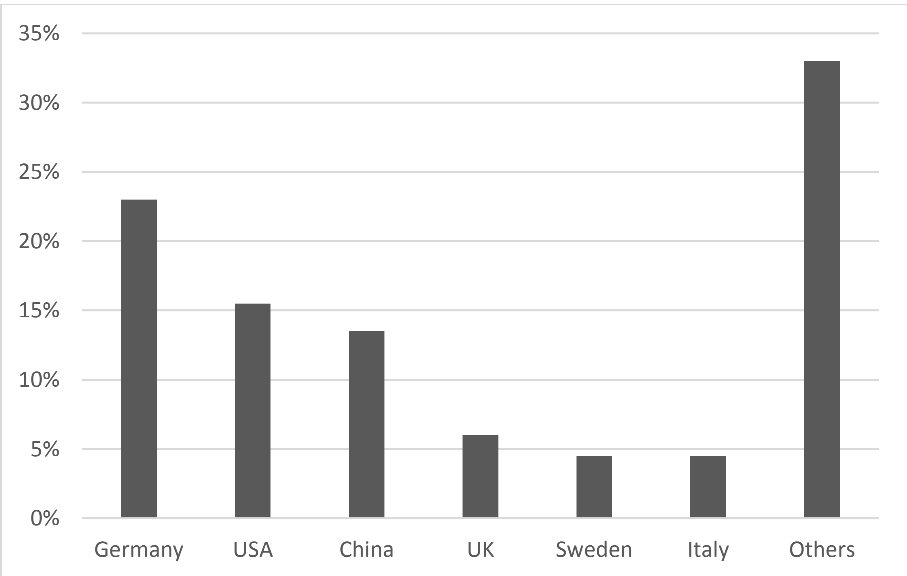
Departments	**Frequency (%)**
Industrial Engineering	17,6%
Mechanical Engineering	15,4%

Electrical Engineering	4,4%
Science and Management	4,4%
Manufacturing Systems	4,4%
Information Systems	3,3%
Integrated Manufacturing Technology	3,3%
Aerospace Engineering	3,3%
Mechatronics Engineering	3,3%
Others	=< 3%

Although the robotics area is one of the first areas to publish on the subject along with Industrial Engineering, it did not present a quantity of articles higher than 3.3% of the total. The departments that were not pioneers, but presented significant percentages of publications since 2005, were the areas of Mechanical Engineering, Electrical Engineering, Management, Integrated Manufacturing Technology and Aerospace Engineering. After 2010, the Manufacturing Systems and Information Systems departments also presented relevant amounts of studies. Thus, there is a growing diversification of departments concerned with studying the theme over the years.

Figure 13 shows the most representative countries in publications on digital manufacturing. Germany, the United States and China together present more than 50% of the publications.

Figure 13 - Publication by country

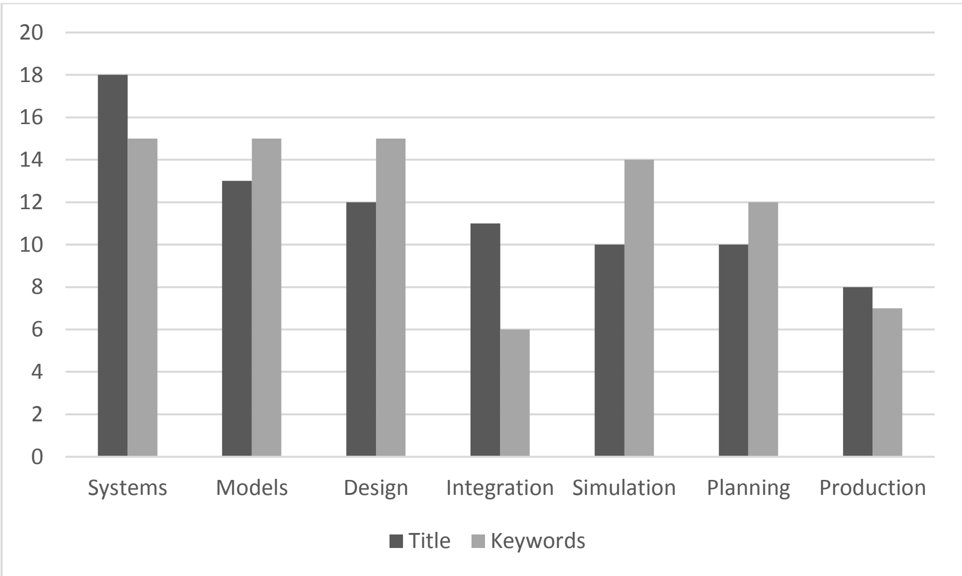


Each country has specific departments dealing with digital manufacturing. In Germany the studies are concentrated mainly in the departments of Industrial Engineering and Manufacturing Systems. In the United States, publications come mostly from Electrical and Mechanical Engineering. The research conducted in China is in the areas of Integrated Manufacturing Technology and Mechanical Engineering.

The cross-referencing of origin data and period of publications concerning digital manufacturing made it possible to analyze the pioneer countries. Between 1999 and 2004 Germany and the United States of America were the main countries presenting studies on the subject. In the period of 2005 and 2011 there is a strong concentration of publications of researchers from China, Germany and England. Finally, between 2011 and 2015 the United States, Germany and Italy stand out in this context.

Given that the keywords of the publications generated a diversified list, in which not many repetitions of terms were obtained, the subjects most frequently mentioned in the titles of the publications were analyzed to group the keywords. For this purpose, the Atlas.TI® tool was used to help counting the frequency of words contained in the titles of articles. Figure 14 presents the topics covered in keywords and titles.

Figure 14 - Topics covered along with digital manufacturing



The most quantitatively representative words of titles and keywords - Systems and Models - are related to different topics and did not include a strong concentration on a specific subject.

One of the functionalities of digital manufacturing is to enable the simulation of an existing process, product or resources, or to find possible improvements, reducing the number of prototypes and avoiding possible future errors. For Rooks (1999) digital manufacturing technology allows the integration of simulation (validation tool) and production planning and control, such as production scheduling and ERP. Kühn (2006) presents that digital manufacturing allows the application of different types of simulation, such as simulation of discrete events and simulation of 3D movements, improving process and product planning at all levels and allowing integrated control from planning to the factory floor.

In this context, Zulch and Grieger (2005) point out that planning is present throughout the product life cycle and its respective production, and integration of the product development and factory design areas enables a harmonious operation, thus, reducing the time between the launch of new products. Support for process and product planning is provided by digital manufacturing through a variety of tools, such as 3D modeling programs and simulations.

The significant presence of the production theme reinforces the application of digital manufacturing in the production processes. Yang et al. (2008) divide digital manufacturing into seven areas: (i) quality management. (ii) virtual assembly planning, (iii) simulation of current production; (iv) layout of the plant; (v) man-machine engineering; (vi) process planning; (vii) validation of productive capacity. Thus, it integrates the development, testing and optimization processes of the product; development and optimization of the productive process; design and improvement of the plant; and production planning and control (Kuhn, 2006).

According to Petzelt et al. (2010), the theme Integration is relevant in the context of digital manufacturing, although it does not present many citations in keywords. The concern about the integration of new digital tools is increasing as new technologies emerge. The implementation of digital manufacturing involves many areas and tools requiring a strong integration, whether Computer-Aided tools or the different departments that impact the project.

The design theme is significant in the two contexts searched. The tools and methods of digital manufacturing can be used in different design activities, such as simulations by different agents involved in the collaborative work (Stef et al., 2013). By facilitating the integration between design and manufacturing engineering, digital manufacturing allows an early view of final product design data (Al-Zaher & ElMaraghy, 2014). Digital manufacturing is also embedded in the design context of the factory layout, in which it can facilitate and support its development. Some concentrations of the study focus by country were found. Publications from Germany and China are strongly related to Planning and Simulation, while Design studies are concentrated in England. The United States, on the other hand, presented a diversity of themes, but it was verified that most of the studies of digital manufacturing with emphasis on 3D printing originated from that country.

4.2 Content analysis

The lack of a clear definition of digital manufacturing and related concepts creates two main problems, both for academia and industry. Theoretically, this lack of clarity in its definition prohibits an effectiveness communication among authors and the evolution of research and applications based on a consolidated body of knowledge. At the same time, at industry applications domain, consequences for managers are even worse. The lack of clarity makes it difficult the tasks associated to plan, design and implement digital manufacturing initiatives. According to Theorin (2017), particularly this makes difficult the task of recruiting the right human resources and planning the required financial resources, Companies are required develop specific digital manufacturing capabilities that are based on complex technologies, techniques and tools. In this case where high-cost technologies and long-term project are involved, this becomes critical.

Since a key terminology confusion is between ‘Digital Manufacturing' and "Digital Factory", it is wise to analyze its definitions. To characterize the main characteristics and main differences between them, a systematic approach to conduct the content analysis was used. The definitions proposed by the different authors from the pre-selected set of papers was analyzed.

From the 93 papers, 20 of them presented their own definitions for the studied terms. With the snowball technique another 34 papers were identified, in which 16 papers have their own definition. Thus, the portfolio used for the content analysis contains a total of 36 papers.

The review performed to analyze the Digital Factory definitions resulted in 23 different and original definitions. Table 12 compiles the different definitions of digital factory given by portfolio authors.

Table 12 - Definitions of Digital Factory

Year	Authors	Definition
2001	E. Westkämper, R. von Briel	"[Digital factory] can be defined as the representation of all data of a factory and the functionality of up and downscaling (micro to macro)"
2003	H. P. Wiendahl, T. Harms, C. Fiebig	"The Digital Factory is taken to be an operational digital model of a real, tangible factory. […] The Digital Factory is developed in four stages: modelling, simulation, presentation and interaction"
2005	S. Wenzel, U. Jessen, J. Bernhard	"The digital factory is the entirety of models, methods and tools for the sustainable support of factory planning and factory operation, including the respective processes (workflow), based on linked digital models (in connection with the product model)."
2005	G. Zülch, T. Grieger	"The digital factory is a network of digital methods, models and tools to support the planning, realization, operation and continuous improvement of a production system with respect to its essential processes and resources."
2005	U. Bracht, T. Masurat	"The object [of digital factory] is to secure products and processes during an early phase of development and also to accompany the evolution of products and production with the use of digital models. Besides that, the extension of the Digital Factory towards internal and external logistics and business processes should enhance the networking and the overall view of the cooperating enterprises."
2006	W. Kuehn	"The digital factory integrates the following processes: product development, test and optimization, production process development and optimization, plant design and improvement, operative production planning and control. The digital factory concept […] can be also seen as an enterprise including an information strategy to manage and integrate the processes of multiple factories in global networks. It offers methods and software solutions for product and portfolio planning, digital product development, digital manufacturing, sales and support that deliver faster time-to-value."
2006	J. Pakkala, F. J. Lopez	"A Digital Factory may be described as a factory system without walls or borders. Resources, both material and human, from different corners of the globe may be linked electronically allowing quick response to either global or local market demands. Software can allow simulation and production planning in one location that may be carried out in one or more locations. Digital factories promise to drastically reduce the time required to reach the market and also drive costs down by optimizing global corporate resources."
2008	P. Butala, et al.	"The digital factory represents an approach to explicit formulation of manufacturing knowledge and it's coding into software. The objective here is to efficiently support design, development and operations of a real factory."
2008	A. Ŝtefánik, et al.	"[Digital factory] represents the environment integrated by computer and information technologies, in which the reality is replaced by virtual computer models. Such virtual solutions enable to verify all conflict situations before real implementation and to design optimized solutions." "[Digital factory solution] … enables quick feedback among designers, technologists, production systems designers and planners. Digital Factory represents integration chain between CAD systems and ERP solutions. One of very important property of Digital Factory is the vision to realize process planning and product development with parallel utilization of common data."

2009	P. Zhao, et al.	"A digital factory offers an integrated approach to virtually run a process without having a real one. Simulation is the key technology within this concept. Event-based, time-based or hybrid simulation models can be built to any degree of details for conceptual system designs required by the analysis."
2009	T. Kjellberg, et al.	"To get the most out of a digital factory model it should be able to mirror the real factory regarding layout, installed equipment and their states regarding capability and maintenance. A core part of the digital factory is machine tool models. Machine tool information is used for many different purposes during the manufacturing system life cycle."
2009	M. Gregor, et al.	"[Digital factory solutions] enables quick feedback among designers, technologists, production systems designers and planners. Digital Factory represents integration chain between CAD systems and ERP solutions. One of very important property of Digital Factory is the vision to realize process planning and product development with parallel utilization of common data."
2010	M. Gregor, S. Medvecký	"The Digital Factory system utilizes 3D digital models of real objects. DMUs". "Digital Factory entitles virtual picture of a real production. It represents the environment integrated by computer and information technologies, in which the reality is replaced by virtual computer models. […] Digital Factory supports planning, analysis, simulation and optimization of complex products production and simultaneously creates conditions and requires team work."
2010	D. Zuehlke	"Digital factory represents the vision for future factory planning, including new system development, planning and control tools. These tools will integrate planning, simulation, operation and even MES and ERP functions supporting the complete product lifecycle."
2010	V. Cheutet, et al.	"Digital Factory is born to design and simulate the production systems in parallel of the product design process. […] One purpose of the Digital Factory is to support the planning process, in case of modifications of the production processes (introduction of a new product or a new work center, modification of the production rate, etc.) with a series of tools, such as, e.g. 3D modeling programs or simulation programs. […] Thus, the dynamic factory occurrences can be played through, analyzed and improved. […] The Digital Factory is based on a large number of very different digital simulation tools, based on various representation levels of the production system."
2011	A. Azevedo, A. Almeida	"[Digital factory] concept involves much more than just the use of simulation tools. It imposes new types of factory organization and an intensive collaboration between the manufacturer and the subcontractors. The data outcome of every step of the workflow should be specified and the levels should be stored in a global factory-wide database. As a final target, it is expected that the development and production will only begin if the respective simulation shows that product and production will meet the given investments, the predefined time schedule and the necessary quality. Therefore, manufacturers have coined the concept ''Digital Factory'' to designate network of digital models, methodologies and applications used to integrate the planning and design of manufacturing facilities with the manufacturing process itself, following the entire life cycle of the factory"
2012	M. Matsuda, K. Kashiwase, Y. Sudo	"A digital factory is a virtual factory and an IT platform for supporting sustainable production planning by executing virtual manufacturing. In other words, in the digital factory, the production scenario is examined by simulating manufacturing processes."
2013	U. Dombrowski, S. Ernst	"The core of the digital factory is the simulation, because users of simulation are able to analyze physically not existing or existing systems without any disturbance of operations."

2013	R.C. Malak, J.C. Aurich	“The digital factory is defined as a set of computer aided methods and tools to provide a virtual production model. “
2014	C.L. Constantinescu, et al.	“Therefore, an important requirement of the Digital Factory is to provide stakeholders with information and knowledge support during decision making activities. This data from the real factory will be available together with data being generated by the Digital Factory tools in the virtual factory during the factory planning process. These combined activities generate a very large data set that is difficult to store, access and analyze. “
2015	P. Polášek, M. Bureš, M. Šimon	“Digital Factory systems represent the next logical step in the gradual creation of tools to support processes across the whole product lifecycle. Already during the planning phase all parts of production system can be verified, so that the subsequent real production of real products will be ensured in terms of quality and in terms of time and cost.”
2016	M. Matsuda, et al.	"The digital ecofactory is constructed on the virtual production line modelling an actual production line which is constructed by virtual machines. An environmental performance simulation strongly requires to model dynamic behavior of machines."
2016	N. Shariatzadeh, et al.	"The digital factory is a model of a planned or real factory used for design, planning and operations"

The review performed to analyze the Digital Manufacturing definitions resulted in 13 different and original definitions. Table 13 compiles the different definitions for Digital Manufacturing.

Table 13 - Definitions of Digital Manufacturing

Year	Authors	Definition
2003	P. G. Maropoulos	“New, commercial systems for product modelling, digital manufacture and PDM are making use of clearly defined data structures for product, process and resource modelling, hence forming an essential information management infrastructure.”
2007	R. Curran, et al.	“[…] methodology proposed for integrated digital manufacturing should include the management of product, process and resource (PPR) data, a core theme of most PLM solutions.”
2007	M. Mahesh, et al.	“Distributed agents need to frequently transfer data with one another. The data, which is denoted as digitalized manufacturing information, basically contains information on the jobs, factories, resources, requirements, accuracies, resource capabilities, etc. The benefit of having digitalized manufacturing information eases the information data flow through the participating agents, thus ensuring seamless data and information transfer between distributed facilities.”
2007	J. Butterfield, et al.	“The construction of a digital manufacturing solution around a central product, process, and resource tree provides a central hub connecting all of the data and information related to manufacturing activities. This enables the simulation of product performance in a cleaner, more integrated environment, where the effects of change on the product, its processes, and resources can be managed quickly and efficiently. It can also be used by anyone who is involved in the product development process from design engineers to manufacturing process planners and

		production engineers. The PPR hub provides a complete, up to date view of the links and dependencies between the products, processes, and resources at any point in time."
2007	E. Westkämper	"Digital manufacturing is a key for adaptation and based on modern tools and techniques for engineering, control, supervision and management in a network."
2008	H. Nylund, K. Salminen, P. Andersson	"The digital manufacturing system is defined as: 'An integrated environment for design and development of products, production systems and business processes.' The digital manufacturing system provides the necessary computer tools as well as digitally presented information and knowledge, in conjunction with human knowledge and skills. The digital information and knowledge exists only once in a formal and up-to-date form. It can be distributed, but is accessible to all related parties regardless of time and location.
2009	N. Duarte Filho, et al.	"Digital manufacturing is an initiative to define every aspects of the design to manufacture process digitally. An open data management platform is a good basis for it. The platform must support multiple disciplines, including product design, analysis, manufacturing, data sharing and communication, etc, relying on advanced technologies such as CAD, CAR, real time 3D simulations, CAM, PDM, CAPP, etc."
2009	G. Chryssolouris, et al.	"Digital manufacturing has arrived as a technology and discipline within PLM that provides a comprehensive approach for the development, implementation, and validation of all elements of the manufacturing process, which is foreseen by researchers and engineers to be one of the primary competitive differentiators for manufacturers. […] In industrial practice, digital manufacturing aims at a consistent and comprehensive use of digital methods of planning and validation, from product development to production and facility planning."
2009	Y. Coze, et al.	"Digital manufacturing is the capability to define and simulate exactly how a product will be built in a glob al collaborative environment. Digital manufacturing allows production engineering staff access to product design at an early stage and also provides a clear view of the production environment. This results in better planning and validation of manufacture processes before a product is built."
2011	J. Lee, S. Han, J. Yang	"Digital manufacturing technology uses integrated digital models created through the modeling of physical and logical components of a manufacturing system and then uses a computer to make a precise simulation of their behaviors. Moreover the technology helps the pre-verification of the manufacturing system in the planning stage for various malfunctions; it also helps in the strategic decision-making across all the manufacturing processes."
2012	J.L. Menéndez, et al.	"[…] the concept of Digital Manufacturing by using PLM tools goes beyond discrete event simulation and embraces the use of a set of tools, allowing interoperability and concurrency between product design and industrial design, to design products, processes and resources."
2014	A. Al-Zaherx, W. ElMaraghy	"Digital manufacturing technologies used to facilitate the collaboration between product design and manufacturing engineering functions, by providing manufacturing engineers earlier visibility to product design data. Afterwards, assessments can take place to evaluate the impact of a given design concept (engineering change) on the manufacturing process operations, identify potential issues, and recommend improvements for the product."
2016	J. Lee, et al.	"Digital manufacturing is a comprehensive approach for the pre-verification in the planning stage or in the strategic decision making across all the manufacturing processes."

Through coding process, it was noted that are a great concentration of several terms used to define ‘digital factory’ and ‘digital manufacturing’. Some terms are not quoted exactly as presented here, but contextually they have similar meanings (e.g. simulation, simulations, simulated, simulate) and were clustered for analytical purposes when convenient. Each of the 23 definitions for Digital Factory uses at least one of these terms. Terms that primarily define characteristics or function are compiled on Table 14.

Table 14 - Most used terms to define Digital Factory

Term	Authors using term
PPR (Product, Process and/or Resources)	Wenzel, Jessen, and Bernhard 2005; Zülch and Grieger 2005; Bracht and Masurat 2005; Kuehn 2006; Pakkala and Lopez 2006; Ŝtefánik et al. 2008; Zhao et al. 2009; Kjellberg et al. 2009; Gregor et al. 2009; Cheutet et al. 2010; Azevedo and Almeida 2011; Polášek, Bureš, and Šimon 2015
Digital model	Wiendahl, Harms, and Fiebig 2003; Wenzel, Jessen, and Bernhard 2005; Zülch and Grieger 2005; Bracht and Masurat 2005; Kjellberg et al. 2009; Gregor and Medvecký 2010; Cheutet et al. 2010; Azevedo and Almeida 2011; Malak and Aurich 2013; Shariatzadeh et al. 2016; Ŝtefánik et al. 2008
Support	Wenzel, Jessen, and Bernhard 2005; Zülch and Grieger 2005; Kuehn 2006; Butala et al. 2008; Gregor and Medvecký 2010; Zuehlke 2010; Cheutet et al. 2010; M. Matsuda, Kashiwase, and Sudo 2012; Constantinescu et al. 2014; Polášek, Bureš, and Šimon 2015
Simulation	Wiendahl, Harms, and Fiebig 2003; Pakkala and Lopez 2006; Zhao et al. 2009; Gregor and Medvecký 2010; Zuehlke 2010; Cheutet et al. 2010; Azevedo and Almeida 2011; M. Matsuda, Kashiwase, and Sudo 2012; Dombrowski and Ernst 2013; Michiko Matsuda et al. 2016
Tools	Wenzel, Jessen, and Bernhard 2005; Zülch and Grieger 2005; Kjellberg et al. 2009; Zuehlke 2010; Cheutet et al. 2010; Azevedo and Almeida 2011; Malak and Aurich 2013; Constantinescu et al. 2014; Polášek, Bureš, and Šimon 2015
Production planning	Zülch and Grieger 2005; Bracht and Masurat 2005; Kuehn 2006; Pakkala and Lopez 2006; Gregor et al. 2009; Polášek, Bureš, and Šimon 2015; Michiko Matsuda et al. 2016; Ŝtefánik et al. 2008
Integration	Kuehn 2006; Zhao et al. 2009; Gregor et al. 2009; Gregor and Medvecký 2010; Zuehlke 2010; Azevedo and Almeida 2011; Ŝtefánik et al. 2008
Design	Kuehn 2006; Butala et al. 2008; Zhao et al. 2009; Cheutet et al. 2010; Azevedo and Almeida 2011; Shariatzadeh et al. 2016; Ŝtefánik et al. 2008
Production system	Bracht and Masurat 2005; Kjellberg et al. 2009; Gregor and Medvecký 2010; Zuehlke 2010; M. Matsuda, Kashiwase, and Sudo 2012; Shariatzadeh et al. 2016
Data	E. Westkämper and von Briel 2001; Gregor et al. 2009; Azevedo and Almeida 2011; Ŝtefánik et al. 2008
Factory planning	Wenzel, Jessen, and Bernhard 2005; Zuehlke 2010; Constantinescu et al. 2014
ERP	Gregor et al. 2009; Zuehlke 2010; Ŝtefánik et al. 2008

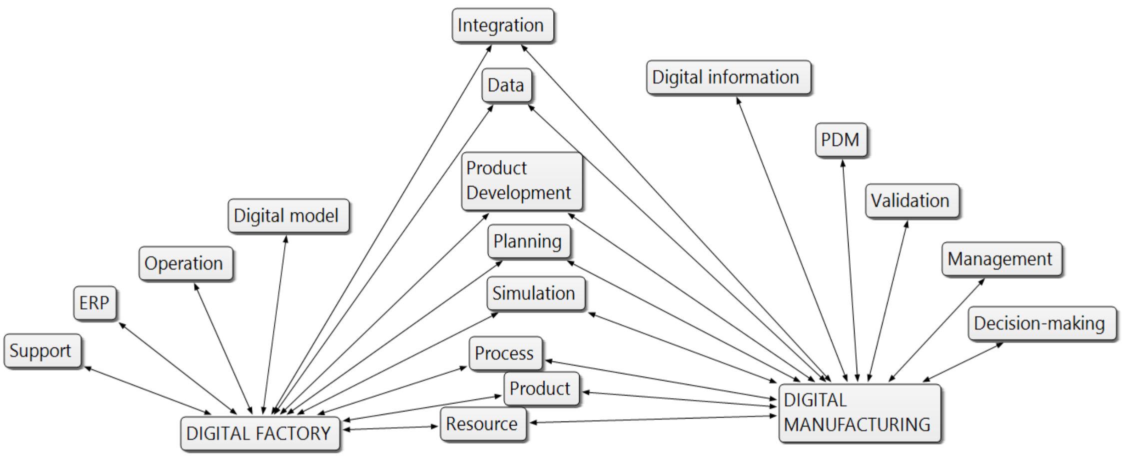
From the analysis of the 13 definitions it was found a concentration of terms that help to define digital manufacturing. As previously stated, some terms were clustered for analytical purposes. Each of the 13 definitions uses at least one of these terms. The terms that primarily define characteristics or function are compiled on Table 15.

Table 15 - Most used terms to define Digital Manufacturing

Term	Authors using
PPR (Product, Process and Resources)	Maropoulos 2003; Curran et al. 2007; Butterfield et al. 2007; Nylund, Salminen, and Andersson 2007; Filho et al. 2009; Chryssolouris et al. 2009; Coze et al. 2009; Menéndez et al. 2012; Al-Zaher and ElMaraghy 2014
Data	Maropoulos 2003; Curran et al. 2007; Mahesh et al. 2007; Butterfield et al. 2007; Filho et al. 2009; Al-Zaher and ElMaraghy 2014
Production planning	Butterfield et al. 2007; Chryssolouris et al. 2009; Coze et al. 2009; Lee, Han, and Yang 2011; Lee et al. 2016
Simulation	Butterfield et al. 2007; Filho et al. 2009; Coze et al. 2009; Menéndez et al. 2012; Al-Zaher and ElMaraghy 2014
Design	Nylund, Salminen, and Andersson 2007; Butterfield et al. 2007; Coze et al. 2009; Menéndez et al. 2012; Al-Zaher and ElMaraghy 2014
Tools	Engelbert Westkämper 2007; Nylund, Salminen, and Andersson 2007; Filho et al. 2009; Coze et al. 2009; Lee, Han, and Yang 2011; Menéndez et al. 2012
PLM/PDM	Maropoulos 2003; Curran et al. 2007; Filho et al. 2009; Chryssolouris et al. 2009; Menéndez et al. 2012
Integration	Curran et al. 2007; Butterfield et al. 2007; Nylund, Salminen, and Andersson 2007; Lee, Han, and Yang 2011
Information management	Maropoulos 2003; Curran et al. 2007; Butterfield et al. 2007; Filho et al. 2009
Integrated environment	Butterfield et al. 2007; Filho et al. 2009; Coze et al. 2009
Validation	Chryssolouris et al. 2009; Coze et al. 2009

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. Figure 15 shows a network based on this content analysis.

Figure 15 - 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 present in the object which 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.

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 their research, but without comprehensive coverage of other definitions or views. Most definitions found in the early years cover only modeling, digitization and information management (Butterfield et al., 2007; Curran et al., 2007; Mahesh et al., 2007; Maropoulos, 2003). 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 aspects. Hence, and based on the analysis presented before, 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 also important to identify what DM is not and how terms often used as synonyms differ from each other. The results show that “Digital Factory” is the technology to capture and represent information to model production systems and available processes in a factory (Malak & Aurich, 2013; Navid Shariatzadeh et al., 2016; E. Westkämper & von Briel, 2001; Wiendahl et al., 2003; Zülch & Grieger, 2005). 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. It is concerned with the representation of the product and process in a digital way, but also 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 (MESA, 2016).

DM is 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 characteristics in common, 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 16 describes terminologies and differentiations on emphasis and key benefits.

Table 16 - Comparison between Digital Factory and Digital Manufacturing

	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

4.3 Technology Integration

This section explores the influence of Industry 4.0 technologies on Digital Manufacturing and presents the digital manufacturing application domain in the context of industry 4.0, which includes the digital manufacturing tools and technologies that can be used for its best use within each manufacturing life cycle phase, as well as contextualize how digital manufacturing operates in this new industrial paradigm.

4.3.1 The influence of Industry 4.0 technologies on Digital Manufacturing

Being Digital Manufacturing under the umbrella of Industry 4.0 technologies and playing the role of to integrate technologies and information throughout the product life cycle, Hartmann et al. (2015) points out that industry leaders agree that digital manufacturing technologies will transform all aspects in the manufacturing systems of value chains. A variety of concepts and solution-components were drawn and studied to fulfill the vision of Industry 4.0, and these technologies have significant influence on current manufacturing (Singh et al., 2015; Sztipanovits et al., 2013). The technologies include Cyber-Physical Systems (CPS) as intelligent entities in production or manufacturing, IoT as communication platform for CPSs, Cloud solutions for decentralized services, and Big Data solutions for high-performance processing of big data in manufacturing (Kagermann et al., 2013; Jay Lee et al., 2013; Sztipanovits et al., 2013). As observed by Rüßmann et al. (2015), many 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, competences, capabilities, skills, and resource based views (Baur & Wee, 2015; Bechtold et al., 2014; Deloitte, 2015; Gartner, 2015; Griessbauer et al., 2016; Heynitz & Bremicker, 2016; Rüßmann et al., 2015; VDI, 2015).

However, the framework developed by the Boston Consulting Group, as presented in Rüßmann et al. (2015), 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 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 digital manufacturing at different stages of the manufacturing life cycle, and impact it in terms of design, implementation, use or management.

To answer research questions, a 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. We explore next how the Industry 4.0 technologies influence design, implementation and use of various digital manufacturing tools. References are used from different fields to provide a comprehensive view, but with a weighting toward the use and application of technologies such as computer and systems science, computer engineering, and cognitive systems.

Each of the next subsections is structured to present four main points:

1. an overview of each technology of Industry 4.0;
2. how each technology is applied together with Digital Manufacturing;
3. how this joint application creates value; and,
4. example(s) of such joint application and its respective phase in the manufacturing life cycle.

Note that the order of technologies presented does not represent the relative weight of contribution in digital manufacturing, since the technologies may influence digital manufacturing in different ways.

4.3.1.1 DM and Simulation

According to Ribeiro da Silva et al. (2018) , digital simulation constitutes a core function in Digital Manufacturing, since it supports experimentation and validation of different scenarios and configurations for existing and new manufacturing resources and systems, contributing for an improved design and performance assessment. Simulation involves modeling of processes or systems, so that the model mimics responses of the actual system to events that take place over time (Schriber, 1974). In a fully integrated Digital Manufacturing 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. Such use of digital manufacturing is already presented in many companies around the globe (Hwang, Lee, Park, & Chang, 2017; Putman, Maturana, Barton, & Tilbury, 2017; Turbide, 2016).

The main difference lies in how simulation is being used today, and at which manufacturing life cycle phase. Digital Mock-ups were the foundation for CAD systems and discrete event simulations for predicting performance. However, the emergence of cloud technologies and real-time data acquisition allows simulations that have migrated from a static and deterministic environment to a more dynamic and stochastic environment. Manufacturing in fact is facing the revival of ‘hardware in the loop’ control systems design techniques.

Real-time scenario analysis involving variables such as machines and equipment conditions, logistical and labor issues, enables simulations to improve targeting and resource selection for a given set of products and processes. The simulation results comprehend scenarios that maximize the use of finite resources available, a significant reduction of waste and line stops, quality improvement and cost reduction. This makes significant difference by allowing analysis of complex scenarios and creating dynamic decision-making mechanisms that is 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).

Sinha et al. (2016) described a case in an automobile company that aimed to synchronize conveyor system and Electrified Monorail System. They used real-time simulation carried out on Delmia for detecting process planning errors. The 3D simulation enabled to verify the motion of equipment's that helped in detecting crashing and trafficking on the assembly line system. Results provide better efficiency of machines and maintained the balance of the assembly line, avoid the trafficking and delay in manufacturing.

4.3.1.2 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. Increasingly, autonomous robots are programmed with artificial intelligence to recognize and learn from their surroundings and make decisions independently. 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. According to Fitzgerald (2017), 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. Palmarini et al. (2018) highlight applications of collaborative robots or 'cobots': robots projected to physically interact with humans in a shared workspace, suited for flexible manufacturing environments since they are designed to be safe to deploy around people without guardian, operating autonomously or with only limited guidance. Cobots not only perform preprogrammed tasks, but also make decisions as necessary when the situation arises.

The main role of autonomous robots in digital manufacturing is to support design and simulation of autonomous or hybrid workstations. Digital manufacturing 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 Digital manufacturing tools adhere to. Several use case simulations are possible and validated through the Virtual Commissioning environment (Rolland, 2017).

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 Stephane (2017) using digital manufacturing 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, in real-time simulations the collaborative tasks between humans and robots DM tools assisted to find the optimal position for the worker in terms of ergonomics and security.

Wadekar et al. (2018) described a task-based risk assessment process conducted in the early stage of layout design and building of a collaborative cell for sealing application performed in aircraft industries using a industrial robot system integrated with safety control functions. According to authors, Digital Manufacturing simulation tools were much required to see the demonstration of the robot task as well as the operator task, use of reachability analysis, creating the robot workspace envelope and dimensioning and positioning of the collaborative system in order to identify the hazards which were possible to eliminate.

4.3.1.3 DM and Cloud

The emergence of cloud computing represents a fundamental change in the way Information Technology 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 (Bal & Tact, 2012; Hackett, 2008; Madhavaiah, Bashir, & Shafi, 2012). According to Mell and Grance (2011), 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. For instance, as pointed out by Wu et al. (2018), 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 computer-aided design (CAD), computer-aided engineering (CAE) or finite element analysis (FEA), and computer-aided manufacturing (CAM) software over the Internet. Thus, manufacturing companies may cut operational and capital costs, and free IT departments to focus on strategic projects rather than keep datacenters running. This type of service outsourcing has emerged as a possible solution to some of the problems encountered for proper use of digital manufacturing.

The use of digital manufacturing technologies requires a robust data infrastructure regarding data storage, transfer, and processing. Data storage is required in large servers, since the files are usually large and in great quantity, while data transfer support network sharing of files in a fast, secure and structured way, mitigating loss of productivity. Finally, high processing power is required for both analysis and simulations that demand high capacity of hardware for execution. Providing the sufficient infrastructure is a key obstacle to the effective use of digital manufacturing, and cloud is an appropriate technology solution.

The main role of cloud technology in digital manufacturing 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 digital manufacturing 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 cloud supports collection and makes data available in real-time for simulation, commissioning and operations management.

An example of application is the Siemens Intosite (2018) that presents a simple and intuitive access to up-to-date digital manufacturing and production information from the shop floor. The solution deploys the digital factory as a software as a service (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.

4.3.1.4 DM and Internet of Things

For Minerva et al. (2015), IoT is mainly concerned with unique identifications, connecting through internet, and given accessibility to “things”. Manufacturing operations have been taking advantage of digital-physical coordination for decades. Evolving technologies are making digital manufacturing more valuable, and the Internet of Things (IoT) is a key element. According to Turbide (2016), 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 digital manufacturing 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 results dissemination obtained to assist decision-making in an efficient and effective way.

The interaction of process and digital product with real-time resources data provides 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 for operational production risks mitigation.

IoT connected 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 that IoT are used within digital manufacturing tools: (i) to allow full process and material synchronization, since plant integration and real-time simulation increases operational excellence; (ii) for predictive maintenance, since providing data for equipment analysis helps prediction accuracy.

4.3.1.5 DM and Big Data & Analytics

Columbus (2015) comments that the manufacturing industry generates more data than any other sector. The more complex a manufacturing operation is, the more valuable the insights gained 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. (2014) 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 backward looking reporting on past events, data is being used to predict trends and anticipate needs (Infor, 2015). 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 (Dassault Systèmes, 2017).

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

Big Data and Analytics are typically employed to better use digital manufacturing 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 digital manufacturing tools more accurately (Dassault Systèmes, 2017).

4.3.1.6 DM and Cybersecurity

Cybersecurity is devoted to safeguarding the availability, privacy, confidentiality, and integrity of digital data stored and/or transmitted in any format over internal networks and/or over the internet. 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. Advantages of digitalization are discussed as ways to improve productivity and competitiveness. But as the degree of digitalization and connectivity increases, systems also become increasingly more susceptible to security vulnerabilities (Jansen, 2016; Liu & Yu, 2011; National Research Council and National Academy of Engineering, 2007).

Wu et al. (2018) highlight that the main role of cybersecurity in digital manufacturing 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 un authorized 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. (2018) 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 part 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.

4.3.1.7 DM and Augmented Reality

Real-world interaction with the virtual world may make digital manufacturing 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, or even videos) rendered onto a real environment (Nee, Ong, Chryssolouris, & Mourtzis, 2012; Raja & Calvo, 2017).

We divided the application of AR in digital manufacturing tools in two main forms. First, AR is a means by which ideas are produced and modeled. The technology assists to produce what is seen in the digital model. The idea is built from the interaction of something real. It can be a prototype of the product or the factory floor, with options for virtual development. This is not limited to the development of products, but also to the development of processes and resources. Second, as scope AR supports the visualization of what has already been produced digitally. Applications for training, implementation and operationalization of processes developed through digital manufacturing technologies are examples of this. In addition, the technology enables feedback from the factory floor.

Several key features of digital manufacturing are related to decision making and validation of both product, processes and resources. AR technology supports this through 3D immersion that enables contextual visualization with parameters of real scenarios and allows detailed analysis. In addition, most of the technologies available today (eg HoloLens, MagicLeap, Oculus Rift, Morpheus) already provide user interaction. This makes the creation, analysis and validation processes more collaborative and integrated.

Thus, the main role of AR in digital manufacturing is to provide an overlay of virtual information onto the real world in real-time, allowing fast, integrated and accurate decision-making. As presented by Nee at al. (2012), 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).

An example of AR application joint with digital manufacturing is presented by Ong et al. (Ong, Pang, & Nee, 2007) 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.

4.3.1.8 DM and Additive Manufacturing

Additive manufacturing (AM) or 3DPrinting is defined by a range of technologies that translate virtual model data into physical models or prototypes. Using AM processes can be conducted directly from 3D design, without the necessity for intermediate process or tooling such as injection molds. The physical object is obtained through a process of depositing successive layers of material of a finite thickness. According to Davia-Aracil and Hinojo-Pérez (2018), AM also facilitates the manufacture of short production series or customized products, even spare parts. The more complex a product and its manufacturing operations are, the more valuable digital manufacturing is. Despite a significant development in AM technology, Paritala et al. (2017) point out that it still requires more insight into the microscopic and macroscopic aspects of manufacturing processes and systems.

The main role of AM in digital manufacturing 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 great precision, resulting in pieces visually identical to the planned product. Adjustments can then be proposed that only would be noticed later on the actual manufacturing assembly line. This reduces time and costs of developing a new model.

Conversely, DM assists in the preparation and validation of AM process to 3D printers. It helps save time and energy by archiving best practices for reuse, automatically optimizes part positions, create supports for developing different strategies for the additive process and implement a variety of 3D printers and additive systems with multiple outputs (3DS, 2017).

For instance, Renishaw (2017) describes the use of digital manufacturing tools to provide printable AM files, aligning virtual and real worlds of 3D design, test and analysis software and metal 3D printing. This aimed to remove the need for the export of native CAD source files in a universal .stl triangulated file format, since it introduced manufacturing errors and was prime cause of loss of quality control. Following an iterative, closed-loop sequence of hinge design adjustment, simulation, printing and precision inspection, the AM built rules to achieve optimal 3D design and printing. As a result, the digital manufacturing tools allowed for printed parts produced more accurately, bringing lead time and material cost savings.

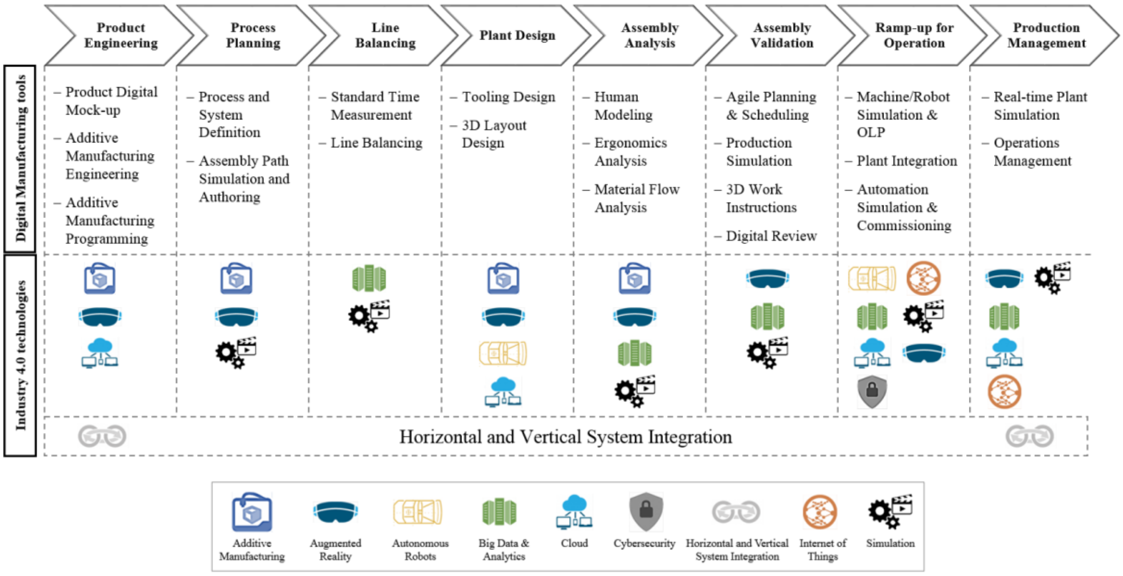
4.3.2 Application domain of Digital Manufacturing in Industry 4.0

The growing increment of technologies that are being made available for industrial use, the technological changes that have been taking place, in line with the new paradigms of production and consumption (such as *servitization*), means that we must address the issue of application domain within a time horizon.

Studies, such as by Noh (2006), present five manufacturing life cycle phases and the presence of DM tools in only three of them. However, the application domain of digital manufacturing was clearly expanded due the new tools offering by DM providers and the rise of several new technologies that can be used jointly with digital manufacturing. Thus, in this study the manufacturing life cycle was divided into eight phases to better understand the function of digital manufacturing tools. These phases are: product engineering, process planning, line balancing, plant design, assembly analysis, assembly validation, ramp-up for operations, and production management.

Figure 16 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 that are 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.

Figure 16 - Application domain of digital manufacturing in Industry 4.0



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 to choose 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 solution providers, such as Siemens with Tecnomatix (Siemens, 2018) and Dassault Systèmes with Delmia (Dassault Systemes, 2018).

As such, the framework provides information on which Industry 4.0 technologies are addressed based on the choice of value package selected. It is noticeable that some technologies can be used in several phases, while others only are used in specific phases. For instance, AR can be used to assist phases from product engineering to production management. In contrast, autonomous robots are mostly used only in the layout planning and the ramp-up for operation phases. Therefore, how solution providers classify tools in three main focuses are partially adjusted to the technologies. The three focuses are: Design-centered DM, which has functions for support design and engineering tasks; Production-centered DM that supports manufacturing preparation tasks; and Control-centered DM which deals with monitor and control by direct interface with production systems and machines on the shop floor. Technologies that focus more on control functions such as IoT and Cybersecurity are only seen in the later life cycle phases. Others which have a design and production function, such as AM, are consequently seen in earlier life cycle phases.

It is noted there is a new range of tools to help plan, integrate and simulate the manufacturing environment. Two key technology characteristics that stand out in are integration and connectivity. Regarding integration, it is worth commenting on three important DM types: vertical integration of processes, horizontal integration of the value chain, and integration of data, tools and systems (interoperability). The vertical integration of processes consists of integrating the processes of different organizational units and making data available and optimized in an integrated network. Horizontal integration stretches beyond internal operations from suppliers to customers and all key value chain partners. It includes technologies from track and trace devices to real-time integrated planning with execution (Griessbauer et al., 2016).

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 allow information management throughout the product life cycle, a main DM function, 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-organizational integration, many organization 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.

However, having all the information integrated digitally brings serious risks, as discussed in the cybersecurity section. For instance, industrial cybersecurity cases of ransomware are increasingly common (such as NotPetya, WannaCry, GoldenEye, etc) and risks are not limited to data loss or capture, or financial risks. There are also, as cited by Sorel (Sorel, Myers, & London, 2017), risks in terms of downtime, reputational, brand and subsequent top-line revenue. Hence, organization becoming digital and integrated must commit to constant cybersecurity vigilance.

4.4 Critical success factors

This section presents the results from pilot case and survey in defining the Critical Success Factors (CSF) for Digital Manufacturing adoption in Industry 4.0 while also discuss several implications pursuing it during implementation process.

4.4.1 Literature Review

During the literature review 70 CSF were initially mapped and after an analysis to refine the list it was possible to compile them in 28 CSF that directly affect the success of DM in the context of Industry 4.0, as is shown on Table 17.

Table 17 - Critical Success Factors for DM in Industry 4.0: Literature Review

Categories	CSF for DM implementation in the context of Industry 4.0	
Technical	TF1	Data management interoperability related to tools and systems integration
	TF2	Infrastructure, operating system speed and ease software configuration (computers, networks)
	TF3	Real-time data
	TF4	Connectivity
	TF5	Ability to transform Big Data into knowledge and decision-making
	TF6	System architecture that support data from IoT
	TF7	Advanced robotics
	TF8	Cybersecurity
	TF9	Traceability
	TF10	Logistic automation
	TF11	Technical support for DM tools
	TF12	Availability of collaborative tools
Organizational	OF1	User knowledge
	OF2	Training programs (project team, support team, decision-makers and users)
	OF3	Collaborative organizations with self-training teams
	OF4	Centralized management of products, processes and resources
	OF5	Dynamic design of business processes and engineering
	OF6	Innovation-driven culture
	OF7	Employee adherence, commitment and participation
Project Management	PMF1	Implementation strategy (communication, planning, scope, objectives, roles, responsibilities, change management and support)
	PMF2	Economic Viability
	PMF3	Financial Resources
	PMF4	Composition of the project team
	PMF5	Internal and external communication
	PMF6	Research and development model change
	PMF7	Support and continuous commitment of top management
Extern	EF1	Partners with knowledge and experience
	EF2	Greater customer focus

The first category refers to ‘Technical Factors’, that is closely related to infrastructure, such as software, hardware, and system configurations, but is poor for Industry 4.0. However, the literature on Industry 4.0 point out new features for improved use of DM, such as traceability, cybersecurity, connectivity and the ability to obtain and treat big data. The second category refers to ‘Organizational Factors’ that cover the economic viability, development of capabilities, and characteristics of organizational culture, such as an innovation-driven environment, rapid responses to new developments, and top management support and commitment for long-term returns. The third category refers to ‘Project Management Factors’ (PMF). This category could be considered an extension of the previous category, since they are organizational factors directly related to the implementation management. It includes factors related to the development of communication skills, enabling a collaborative environment and dissemination of the implementation strategy, which is closely related to change management. The fourth and last category refers to ‘External Factors’ (EF) that cover the integration with external suppliers, partnerships with companies to exchange knowledge, greater focus on customer needs, and a government macroeconomic analysis to understand the feasibility of project implementation.

4.4.2 Pilot case

The pilot case resulted in 20 difficulties related to the daily work considering DM concepts and tools. To contextualize them in the CSF it was necessary to identify the root causes of the problems. Twelve interviews were carried out with employees from different departments that encompass: product and process engineering, layout development, equipment development and IT. The departments are consulted for capturing a complete and systemic view of the company situation in relation to DM. Open questions are used, allowing each interviewee to present their vision and experience on the difficulties found in DM implementation. Table 18 lists the difficulties and classifies them according to the four categories of the Risk Breakdown Structure (RBS) proposed by PMI.

Table 18 - List of difficulties

Difficulties		**Freq.**	**Tech.**	**Org.**	**P.M.**	**Ext.**
1	Data network does not meet the minimum requirements	7	X			
2	Lack of specialized training	5		X		
3	Hardware does not meet the minimum requirements	4	X			
4	Lack of tools integration	3	X			
5	Lack of technical knowledge	3		X	X	
6	Low productivity	3	X	X	X	
7	Poorly defined scope for DM project	3		X	X	
8	Lack of internal integration with stakeholders	2			X	
9	Limited licenses	2		X		
10	High financial investment	2		X		
11	Learning process to use DM technologies demands a lot of time	2		X	X	
12	High workload does not allow innovation activities	2		X	X	
13	Cultural barriers	1		X		
14	Lack of tool support	1	X			X
15	Bureaucracy for decision making	1		X		
16	Government aspects	1				X
17	Lack of collaborative tools with suppliers	1	X			X
18	Data management	1	X			
19	Poor communication	1		X	X	
20	Lack of standardization for new technology utilization	1			X	

Most of the difficulties pointed out during the interviews come from poorly implemented CSF already found in the literature and consulting reports. Three factors were added to this list: rapid responses to market technological developments, Workload management to enable innovation activities, and integration with external suppliers.

Although DM is considered a technical matter, the influence of organizational factors is critical. The difficulties related to understanding the project scope and workload planning evidence this fact. However, technical issues also need attention because they directly affect user performance. Even though not all CSF mapped in the literature have been cited in the interviews, it is necessary to consider them in DM implantation strategy.

It has become evident during the interviews most of the difficulties pointed out regarding digital manufacturing are related to basic implementation requirements, such as system understanding, training, workload and infrastructure. It was also clear that complex factors, such as architecture for IoT data, cybersecurity and integrated management were not mentioned because it is still far from the daily reality of the employees.

Thus, it is noticed there is a low maturity of DM implementation, although it has started the process 2 years ago. One of the key difficulties found is the misunderstanding about the real purpose of digital manufacturing. A clear project scope definition, difficulties and benefits in each phase, besides specialized training in the early stages of the project have showed primordial for a successful implementation.

Of the 28 factors identified in the literature review, 13 are also cited as critical during the pilot case. Most of these are related to the organizational dimension. In addition, three new factors are added, as shown in Table 19.

Table 19 - Added factors after pilot case

Categories	**CSF for DM implementation in the context of Industry 4.0**	
Organizational	OF8	Rapid responses to market technological developments
	OF9	Workload management to enable innovation activities
Extern	EF3	Integration with external suppliers

Two of the added factors are organizational and the other a external one. Content analysis shows that the root cause of many problems during DM implementation are due to a lack of appropriate environment, as well as a very slow response to market developments. This is correlated both with the lack of innovative environment, and with political aspects that are external to the company. An example of the latter is protectionist strategies, which make it difficult for companies to acquire certain technologies. The difficulty to work jointly with suppliers in an integrated platform give rise to the last external factor. After the exploratory case, 31 factors constituted the critical factors list.

4.4.3 Survey

Having reduced the anchoring problem in the first phase, a survey questionnaire is developed for the second technical factor refinement. A questionnaire test is carried out to ensure the data collection is applicable in a real-world scenario. The test is conducted according three key groups: (i) users from industry that use various DM tools; (ii) consultants who assist on DM implementation processes, and (iii) researches exploring DM use. The survey is then applied to professionals working with digital manufacturing. The survey is more comprehensive than the test, since it incorporates a greater variety of respondents, such as users, managers, implementers and researchers on digital manufacturing and Industry 4.0 from several countries, enterprises, and research institutes. This has the benefit of supporting the capture of the broader organizational changes related to technological change.

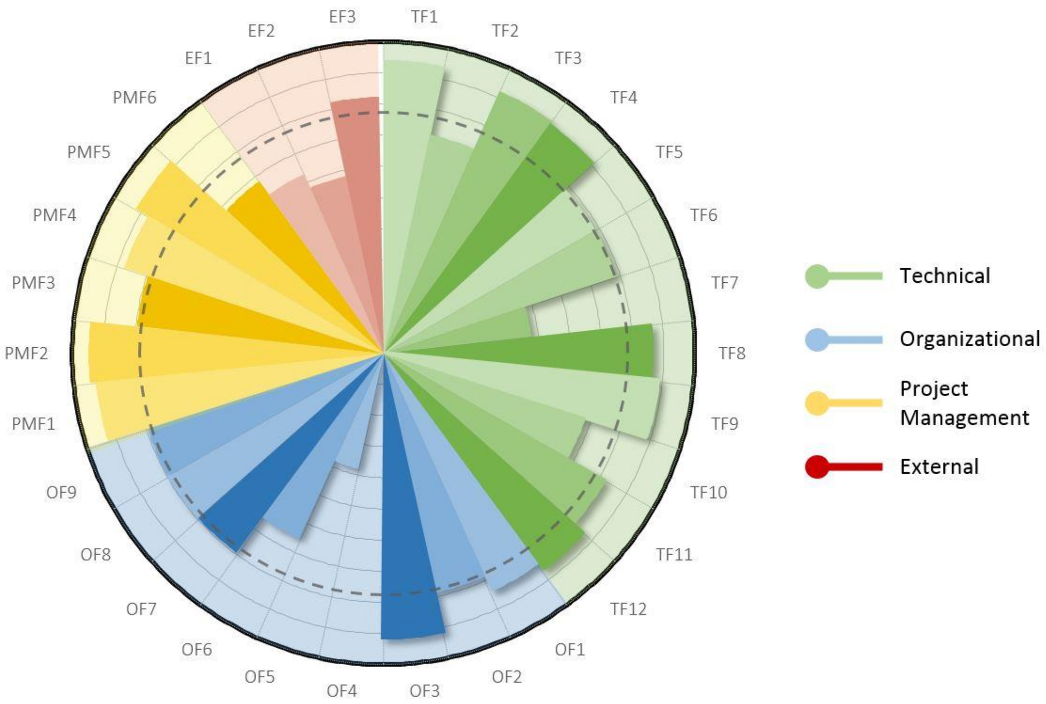
The questionnaire contained 31 questions and is divided into five blocks: (1) sample characterization; (2) questions related to technical aspects; (3) questions related to organizational aspects; (4) question related to project management; (5) questions related to external aspects.

More than 70% of the respondents answered that they have high knowledge (competent or expert) in the subject. Only 6% declared themselves novices or advanced beginners. Most of them work on Production Planning and Simulation (63.9%), 3D Layout Design (40.2%), Product Digital Mock-up (37.1%), Machining Simulation (31,9%) and Material Flow Analysis (27.9%), Human Modeling and Analysis (26,8%). More than 90% of respondents work with more than two DM tools. This information is important since it shows respondents work in the three phases of digital manufacturing: Design-centered, Production-centered, and Control-centered.

Of the 12 technical factors identified, 9 of them had above-average concordance and, according to respondents, are essential for successful implementation and use of DM tools.

Factors related to interoperability (94%), real-time data (92%), connectivity (91%) and traceability (89%) have the highest concordance regarding their neediness for DM adoption. TF2 (71%), TF7 (48%) and TF10 (68%) are out of the cutoff point (See Figure 17).

Figure 17 - Survey results



However, despite TF2 – that refers to the requirement of a better infrastructure and operations system speed than is commonly found on the shop floor for DM tools to work properly – obtained 72% of concordance, it is worth noting that 24% of the academics and researchers group selected the option 'neither', meanwhile respondents from the industrial and consulting environment, who deal directly with the technological difficulty related to day-to-day processing time, present a rate of concordance over 88% and only 3% disagreed. From this more contextualized data analysis it is possible to infer that this factor did not reach a high level of concordance because it directly is related to unfamiliarity of this technological requirement by academics. Because of this, TF2 is added to the list.

Organizational factors are not only bounded by DM implementation, but they are also required for its use and optimization. Survey results show that of the nine organizational factors identified, seven of them presented above-average concordance. Factors related to user knowledge (84%) and employees commitment (95%) appeared with the highest rates. Factors OF5 and OF6 are removed, since they are mischaracterized as critical factors.

Factors categorized as project management could be no longer critical after the technology implementation, since they are not required to operate and optimize the use of the technology. Of the six PM factors identified, five of them had above-average concordance as being critical for a successful implementation. PMF6 is the only project management factor with a relatively low rate of concordance, being removed from the list.

Finally, regarding external factors, only one out of three factors had concordance above the cut-off point. Results show that the only external factor that is critical is the integration with external suppliers (EF3). EF1 which refers to a requirement of partners with knowledge and experience in DM, had 30% of neutral responses. This rate is even higher among the group of consultants, which over 50% respondents providing a neutral response. These numbers are worth mentioning because there they show that rather than a disagreement, there is an apparent neutrality. This let infer that such partnerships are not essential for the success of the implementation and use of DM, despite in some cases create value added. The factor EF2 shows similar results, referring to the need for greater customer focus, which presented 36% neutral answers. This factor also had low rates of discordance.

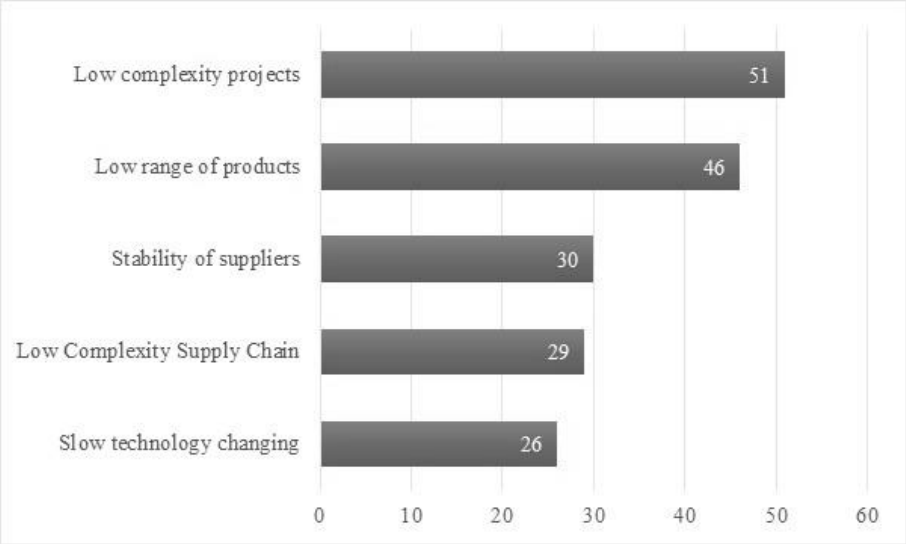
In summary, of the 31 factors initially identified, 24 of them are considered by survey respondents as critical to the success of the implementation and use of DM in Industry 4.0.

4.4.4 Trade-offs for DM adoption in SME

The survey results show that 93 (82.3%) of 113 interviewees agree that digital integration with supplier through digital manufacturing systems brings long-term benefits to the company. Among the benefits, it can be mentioned, for instance, the integration of data into a unique platform, which makes for a more efficient project coordination, allowing up front identification of problems before suppliers deliver the final product. This helps both in reducing rework and the risks involved in the project. Other benefits are also related to cross-enterprise transparency of information, such as the incorporation of both internal and external supplier information, coordination or integration across supplier management process, quality control, and manufacturing decentralization.

However, when asked about appropriate conditions, the results reveal that the implementation of digital manufacturing systems is only feasible under certain conditions, mainly because of systems' complexity and cost that may not be aligned with the company conditions. 104 (92.1%) of 113 interviewees pointed out one or more organizational characteristics where digital manufacturing is not an appropriate solution for the company. Figure 18 shows the most cited conditions by the interviewees.

Figure 18 - Conditions most cited as not appropriate for DM use



The low project complexity was the most commonly cited condition, having been cited 51 times. This was followed in order by the low range of products (46), stability of suppliers (30), low complexity supply chain (29), and slow technology changing (26). Digital manufacturing systems are designed to deal with projects that need to align and integrate data and processes with 3D technologies. The obtained survey results are coherent with such DM theory, since it posits an increased manufacturing intelligence in environments where variables cannot be well predicted or the effects of second order are too complex to be analyzed in a static way. It is also worth noting that operating under some of the conditions does not make the use of DM unfeasible, but being under several of the conditions may make DM implementation and use unfeasible in practice. For instance, in the aerospace sector almost all organizations use digital manufacturing systems. These organizations have both highly complex projects and supply chains and rapid technology change, but the range of products are low and supplier stability is high.

These different characteristics among companies in the same value chain create trade-offs for those seeking digital integration, such as reduced time-to-market and manufacturing decentralization. As cited by Stark (2018), reduced time-to-market drives significantly benefits for a company, such as efficient managerial practices, increase margin revenue, gain market shares, among other benefits that make the company be one step ahead of the competitors. Strategies that large organizations have used to reduce the time-to-market is to have a greater focus on its core business, decentralize manufacturing, and also to digitize the supply chain (Ehrhardt & Behner, 2016; Siepen, Bock, & Marwaha, 2018). 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 (Whyte, Stasis, & Lindkvist, 2016). However, this decentralization also creates some barriers in relation to the anticipation of project phases. One of the benefits that digital manufacturing systems can provide is breaking these barriers by allowing agile manufacturing strategies to connect and to integrate various parts of the manufacturing process. Digital integration with suppliers within a common platform allows the anticipation of several phases of the project. For instance, considering the manufacturing lifecycle, the integration of suppliers allows the product assemblability 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 could anticipate their activities in their projects. However, achieving such benefits requires increasing integration and connectivity with the suppliers.

This means that large companies that develop complex projects have sufficient incentives to use digital manufacturing systems by pursuing time-to-market reduction, as well as having the resources required for their adoption. However, the same incentives are not seen on the (primarily SME) supplier side, that develop a small number of products, do not have the same project complexity, and often being suppliers of competing companies that do not meet the same standards or do not use the same systems.

Thus, it can be seen a paradox in the obtained survey results. Although there are clear benefits of digital integration of suppliers using digital manufacturing tools, implementation and use of digital manufacturing systems is not compatible with most supplier capabilities due to the high cost and complexity of adopting the technology. This means that in the long term there is a likely conflict of interest between the companies.

In this way, some incentives beyond financial returns must be created to make the digital integration feasible. For instance, one of the plausible solutions would be for the contracting company to provide the system and specific training in the tools needed for its main suppliers. The cost to the contracting company is relatively low and may provide several advantages, such as improvement in the project quality and the final product, traceability of the development process, anticipation of project phases and improvement in the long-term supplier relationship.

Despite DM system providing appropriate features for suppliers' integration and many large enterprises adopting it, there are few incentives for SMEs, which also happen to compose the majority of the suppliers, to adopt the technology due high complexity and cost. This, could create a conflict of interest between large companies and their suppliers in the long run. To solve such conflicts, incentives must be created beyond short term financials, breaking the buyer-supplier paradigm and encouraging longer-term partnerships. Moreover, it is noteworthy that the conditions prohibiting digital manufacturing systems are found where adoption most likely would be successfully adopted. For example, where environmental complexity is low the implementation complexity is also low and thus more manageable. But due to the cost and complexity of DM technology adoption, the returns are poor for those companies. An external market change could be required, to reduce the cost of adoption or addressing the right incentives, for example, supporting further SME adoption, since market characteristics are a greater barrier than technological ones.

4.5 Framework development

Seeking to fill the gaps in the literature and to explore the systematization of the critical success factors for its adoption, several interviews were conducted for a contextual analysis. The results show the many aspects that interfere in the success of adoption and contrast different perspectives, approaching studies in different contexts, segments and strategies used. Next sections present the PPDIOO DM meta-framework, DM framework proposition, as well as the capabilities and deliverables for operationalizing the framework.

4.5.1 PPDIOO Digital Manufacturing meta-framework

In exploring a suitable DM framework, this section presents a meta-framework to reflect the various phases of a DM life cycle in the Industry 4.0 context that is analogous to the PPDIOO methodology proposed by Froom et al. (2010) that is applied to reflect the various phases of a typical network's life cycle. PPDIOO is an acronym for Prepare, Plan, Design, Implement, Operate, and Optimize. The use of a lifecycle approach provides several key benefits, such as lowering project total cost, improving business agility and planning for infrastructure changes and technology requirements. Each phase is defined below according to its specific DM purpose:

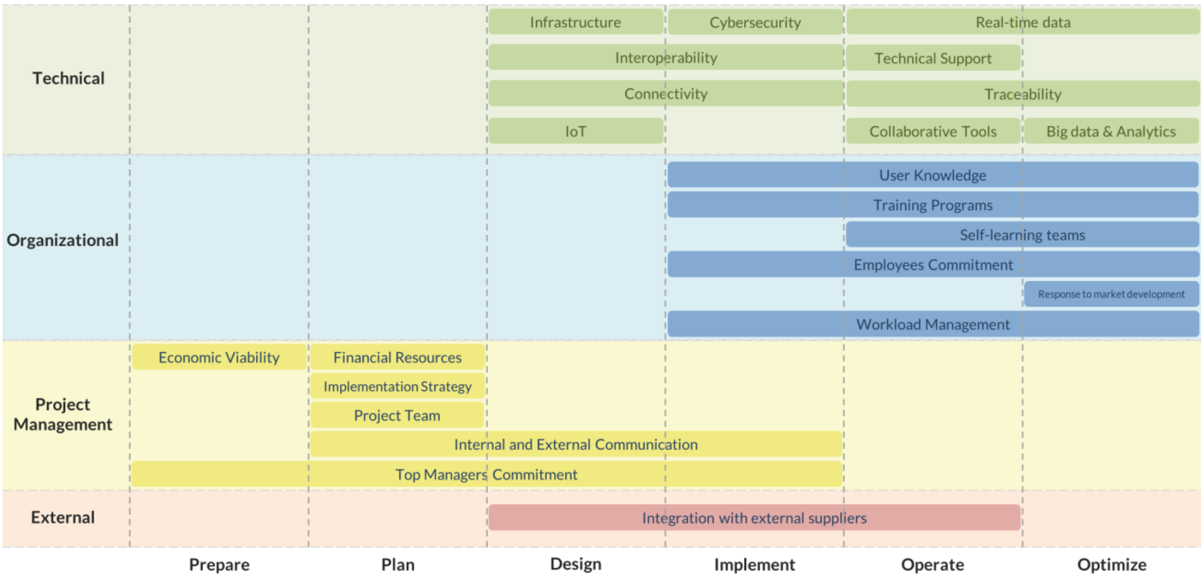
- **Prepare:** Define viability of using digital manufacturing tools. This preparation includes alignment of top management with demanding resources, organizational changes and long-term goals;
- **Plan**: Project planning in its managerial, financial and strategic phases;
- **Design**: Implementation project design in its techniques and forms of applicability within the pre-determined scope in the previous phase;
- **Implement**: Implementation of the DM system and training for appropriate use;
- **Operate**: Projects running with digital manufacturing tools in a connected and integrated way internally and externally.
- **Optimize**: Use of resources to optimize the ongoing operation process, aiming at the implementation of new ways of delivering value through DM

Defining the specific purposes supports the research protocol development that is presented in the following section. The phase purposes are also the basis for the proposed deliverables the results generate. Since unique organizational culture typically has significant influence in DM implementation, detailed implementation recipes tend not to work. Thus, each phase seeks to present a logical structure by which factors should be extensively discussed among the stakeholders.

4.5.2 Digital Manufacturing Framework Proposition

The DM Framework proposed in Figure 19 is composed of four categories, six phases, and twenty-four critical success factors. Each factor is related to one of the categories of technical, organizational, project management, and external aspects.

Figure 19 - PPDIOO DM Framework



Investigating the cases revealed that aspects related to the first phases of DM adoption process are directly related to the project management category, so a feasibility analysis as well as an implementation plan should be carefully developed. This is similar to other technology adoption projects, with a key difference is in the need to change working methods. The implementation phase tends to be more extensive than the preparation and planning phases, while the operation and optimization phases are continuous. Note that the linear representation of the stages shown in Figure 19 does not represent an accurate timeline. The time lengths vary during the phases, and even change from one organization to another.

What makes this type of technology adoption project unique is the extensive culture change and work methodology that needs to occur. It is not just about changing the technology base, but about radical changes throughout the product life cycle, directly interfering with how and when each activity could and should be done. As such, it has more in common with process focused implementations such as lean and agile than with technology specific adoptions such as integrated IT systems (AlManei, Salonitis, & Tsinopoulos, 2018; Rasnacis & Berzisa, 2017; Stachowiak & Oleśków-Szłapka, 2018). The study findings show that since organizational culture has significant influence on the implementation, detailed implementation recipes tend not to work. But for each adoption stage, the results indicate particular aspects and deliverables that need to consideration by the stakeholders involved in the implementation process.

The results also provide also two main insights. First, some lessons can be learned from previous projects that assist to apply the DM framework considering the main aspects and phases that organizations need to manage when adopting DM. Second, the research results generated deliverables for moving between the DM adoption phases. Both are addressed in the next sections.

4.5.2.1 Digital Manufacturing Framework capabilities

Previous projects of technological implementations such as ERP and other legacy systems, as well as process focused implementation such as lean and agile, support the DM adoption due to many shared critical factors and required capabilities. Sedera and Gable (2010) identified the importance of knowledge management to achieve enterprise system success, being the lack of sufficient support from knowledge management approaches throughout the project lifecycle one of the main reasons for implementation failures. An effectively managing a wide range of knowledge, which resides in multiple stakeholders has been identified as a crucial factor for enterprise system project success (Jayawickrama et al., 2016; Lech, 2014). Thus, previous experience an organization adopting complex systems or technologies, such as an ERP system, is helpful for development of conditions such as accurate project planning and employee commitment to new work method. Studies show that several CSF are the same for adopting both systems. Both demands complex and detailed knowledge for successful implementation, being important to discover innovative methods, techniques and approaches that can integrate such knowledge among individuals and across stakeholder groups (Berraies, Chaher, & Yahia, 2014; Ram, Corkindale, & Wu, 2013). Besides that, integration, interoperability and connectivity all play important roles in DM framework as support for organizational change. Operational and organizational capabilities related to these issues need to be developed and have weaker links to legacy systems. Pursuing a single robust and up-to-date data source, fast and reliable data access, and internal and external integration with suppliers all support digital manufacturing. It also enables inter-departmental collaboration and facilitates an accurate and fast decision process which reduces rework in the final project phases.

In contrast, some criteria are specific to DM projects. Issues related to the acquisition, processing and analysis of real-time data to run dynamic and stochastic simulations are not required by other systems. Thus, the importance of the development of capabilities related to real-time data, fully connectivity and IoT devices differs from other technological adoptions. By having technological convergence with other advanced manufacturing technologies, rapidly response to new market developments is also a unique feature of DM projects. The dynamic environment and rapid technological changes are not comparable to the gradual and slow moving that occur with legacy systems.

In this sense, it presents characteristics more similar to process focused implementations such as lean and agile, which other capabilities can be exploited. First, agility is capability that allows thriving and prospering in dynamic, turbulent environment. The capability that makes organization able to respond to changing and differentiated requirements of customers, deal with competitive environment, evolving technologies and decreasing product lifecycles. (Stachowiak & Oleśków-Szłapka, 2018). Factors such as supply chain integration, leadership commitment and employee involvement in complex projects, developed communication channels intra- and inter-departmental, changing working culture can be cited similar success factors (AlManei et al., 2017; 2018). R&D capability has an important role in absorbing knowledge generated elsewhere, and also refers to the capability to undertake frontier technology activities Moreover, upskilling and technological capability development are also indispensable (Radosevic & Yoruk, 2016, 2018).

Several capabilities ranging from technological to managerial should be developed to conduct such projects in the context of Industry 4.0. They are related to production, technological and innovation capabilities. The accumulation of technology embodied in successive generations of increasingly advanced physical capital, together with the accumulation of the associated human capital required to operate the production system efficiently represents the production capability. Lastly, the ability to create new technology, design new features of products and processes represents the innovation capability (Bell & Figueiredo, 2012; Radosevic & Yoruk, 2016; Szalavetz, 2018). To succeed in the DM operationalization and optimization, as well as for other advanced manufacturing technologies, it is pivotal organizations develop capabilities in these three dimensions seeking long-term learning skills.

4.5.2.2 Digital Manufacturing Framework deliverables

Readiness is the extent to which an organization assesses that the project ran smoothly and problem free when it looks backwards at the end of project. In practical terms before the project starts, the overall readiness is also a measure of the extent to which the organization has put in place the employees' skills, resources and other factors which are necessary for the project to proceed smoothly and problem free. To develop the project plan for improving the readiness, the organization initially needs to know which activities should be performed to achieve readiness and what is the current state of readiness in the organization (Ahmadi, Papageorgiou, Yeh, & Martin, 2015).

Hence, for each phase of the DM adoption process to be successful, some minimum requirements need to be met. Based on the proposed framework and developed cases, a set of deliverables for each phase of the process is proposed below. Due to be a sequential process, it is important that each stage meets these minimum requirements to minimize the risks of project failure. Table 20 shows the deliverables for each phase.

Table 20 - Deliverables for the PPDIOO DM Framework

Phase	Purpose	Deliverables
Prepare	Define viability of using digital manufacturing tools. This preparation includes alignment of top management with demanding resources, organizational changes and long-term goals.	– Economic viability analysis verifying characteristics that justify DM use and implementation, such as project complexity, product range, supply chain extension and stability, speed of change of technology – Meetings with top managers to ensure project commitment for long-term benefits
Plan	Project planning in its managerial, financial and strategic phases	– Design the strategic plan for implementation, involving scope, objectives, responsibilities, communication channels and support – Release financial resources – Definition of responsible project team
Design	Implementation project design in its techniques and forms of applicability within the pre-determined scope in the previous phase	– Definition of infrastructure needed to implement the project – Design of systems integration – Design of integration with external suppliers – Design of integration with the shop floor *(if applicable)*
Implement	Implementation of the DM	– Context presentation meetings for users addressing

	system and training for appropriate use	mid and long-term benefits for the company and users, and the difficulty of changing the way working. The commitment of users to the new way of working is a goal – Training programs for selected tools in scope – Implementation of accesses and security of internal data. Includes deployment of network firewalls, local firewalls, and application firewall for external security
Operate	Projects running with digital manufacturing tools in a connected and integrated way internally and externally)	– New projects delivered within DM system applying available tools
Optimize	Use of resources to optimize the ongoing operation process, aiming at the implementation of new ways of delivering value through DM	– Structuring periodic analysis of market developments and its DM applicability – Structured and periodic analysis of data collected to improve DM utilization and seeking new ways of delivering value through DM

As presented earlier, the transition time between each phase varies depending on the organization and project scope. But is the deliverables and their assessment must be completed before commencing the next phase. Such validation process increases process reliability and aligns expectations. Validation with top managers helps ensure commitment to the project as well as the resources for later phases of the project.

5 CONCLUSION

This chapter presents the conclusions by analyzing the research questions and exploring the research objectives. This also presents theoretical and managerial contributions, research limitations, and recommendations for future researches.

RQ1. What is the scope of application of Digital Manufacturing in Industry 4.0 and what differs it from other concepts?

The first research question comprises two research objectives. The first one is to **characterize and define content and scope of digital manufacturing application in Industry 4.0**. However, to define the scope and non-scope for DM was primarily necessary to understand the definition of DM that is not very clear in the literature. A systematic literature review and content analysis assisted defining what DM is and what differentiates it from other terminologies that are constantly used as synonyms in both academic and business environments. The results showed that digital manufacturing extrapolates the digital representation of resources and processes and plays a key role in integrating technologies and business areas focusing on improving the entire manufacturing life cycle. An updated and holistic definition for digital manufacturing is presented.

With this first results it was possible to explore the second research objective to **identify how Industry 4.0 technologies are influencing digital manufacturing**. Studies such as Noh (2006) present an application domain for digital manufacturing, but the results in this study have clearly shown that this domain has been expanded in recent years due the increased computing power and the advanced manufacturing technologies. The new characteristics of digital manufacturing refer to integration and connectivity, creating a dynamic environment to design, redesign and analyze the factory, the product and the manufacturing process. The currently available digital manufacturing tools comprise the entire manufacturing lifecycle and several Industry 4.0 technologies can be applied jointly with these tools to add value to the production process. Many of the technologies are not new, but recent forms of integration, improvements in use and joint use have changed the DM field, opening up several new opportunities. This is important because presenting a clear and well-defined application is essential to create, plan and conduct successful DM implementations.

RQ2. What are the critical success factors for the implementation and use of digital manufacturing in Industry 4.0?

The third research objective is to **define the critical success factors for the implementation and use of digital manufacturing in an Industry 4.0 context**. A multimethod approach was used to deal with this objective. Results from the literature review, a preliminary case study and a survey with specialists assisted defining the CSF. In answering the second research question, the three-fold steps allowed to synthesize a set of 24 critical factors for DM adoption categorized by the four categories on the Risk Breakdown Structure. The categories are technical, organizational, project management and external factors.

Exploring the results about the CSF, several conclusions can be draw. First, it became clear that several technologies provide competitive advantages but are not critical for a successful implementation and use of Digital Manufacturing: Technologies associated to Industry 4.0 do have the potential to substantially change the manufacturing processes. They could increase the value added of projects when used in conjunction with digital manufacturing. However, some of them are not intrinsically critical for an implementation nor for its later use. They also need a specific context for their value to be captured. But, note, the fact that certain technologies are not essential for DM implementation does not invalidate the argument that they could bring competitive advantages. In addition, their adoption has allowed some factors not to be more critical, such as the centralization of product, process and resource information, where decentralization of this management along the supply chain is already a positive factor.

Second, the more substantial the knowledge of DM, the greater the value obtained by the joint use with Industry 4.0 technologies. The results indicate that the higher the users knowledge, the greater the concordance that such technologies improve the results obtained from the joint use with DM. This relationship is not surprising but corroborates the alignment perspective among the new characteristics of digital manufacturing and Industry 4.0. Although DM has existed for more than 30 years, its current characteristics are recent and closely related to the pillars of Industry 4.0: connectivity, integration, decentralization and virtualization.

Third, trade-offs are found among the factors even among factors validated as critical for the implementation and use. Since the integration with external suppliers depends on the systems interoperability, if the systems are the same, the exchange of information and the use of collaborative tools is allowed otherwise there could be limitations. In practice, DM systems that meet the demand of required features by large enterprises and enable internal integration, in terms of cost are prohibitive for SMEs. This shows a trade-off related to internal and external integration, based on the economic perspective of the supply chain. Another example is related to rapid responses to market technological developments and cybersecurity, since the guarantee of cybersecurity for new technologies implementation is not something rapid or easy to reach mainly in complex environments.

Finally, it was clear that DM adoption is not only related to technical issues, but also deals with organization changes. Organizational capabilities need to be managed, as the employees' capabilities.

RQ3. How to conduct the implementation and management process of digital manufacturing in Industry 4.0?

The fourth research objective is to **develop an appropriate framework for the implementation and use of digital manufacturing in an Industry 4.0 context**. This study provides a tailored framework to support the process of implementation, use and management of digital manufacturing based on data from six multinational companies. Grounded in theory and empirical cases, the study defined project phases and which factors are vital in each of these phases and systematized the deliverables for appropriate project operationalization and management.

A framework composed of four categories, six phases, and twenty-four critical success factors is proposed. Each factor is related to one of the categories of technical, organizational, project management, and external aspects. This helps understanding which activities managers must undertake to successfully employ DM in an Industry 4.0 context.

What makes this type of technology adoption project unique is the extensive culture change and work methodology that needs to occur. It is not only about changing the technology base, but it is also about radical changes throughout the product life cycle, directly interfering with how and when each activity could and should be done. As such, it has more in common with process focused implementations such as lean and agile than with technology specific adoptions such as integrated IT systems (AlManei et al., 2018; Rasnacis & Berzisa, 2017; Stachowiak & Oleśków-Szłapka, 2018).

In answering the third research question, the study findings show that since organizational culture has significant influence on the implementation, detailed implementation recipes tend not to work. But for each adoption stage, the results indicate particular aspects and deliverables that need to consideration by the stakeholders involved in the implementation process. Thus, a set of deliverables for each phase of the process is proposed. Due to be a sequential process, it is important that each stage meets these minimum requirements to minimize the risks of project failure.

Having explored all specific research questions, the main research question regarding the role of digital manufacturing in Industry 4.0 is explored next.

MRQ "What is the role of digital manufacturing in the context of industry 4.0?".

As presented earlier, DM stands out by combining conventional manufacturing technologies with digital techniques. In short, Digital manufacturing is a set of tools used to design, redesign and analyze the factory, product and manufacturing process in an integrated way.

Although DM already is in use for several years, there have recently been several technical changes and their application domain in production. This is mainly driven by the new industrial context and the rise of advanced manufacturing technologies. These changes led, for instance, the European Commission (EFFRA, 2016) to position DM as one of the five key priorities for the FoF 2020 - Factories of the Future - the strategic proposal presented under the Horizon 2020. This seeks to encourage some implementation initiatives in synergy with the ongoing waves of Industry 4.0. According to them, DM enables the provision of services that support manufacturing in a broad sense.

Due to these changes, the recent forms of integration, the improvements in use and the joint use with another advanced manufacturing technologies, it is noticeable that the DM technology role has changed, as seen by the expansion of the DM application domain. Based on new technologies and the integrated ways of applying them, DM provides comprehensive advantages in all manufacturing life cycle phases. Two key technology characteristics that stand out are integration and connectivity. There is a new range of tools helping to plan, integrate and simulate the manufacturing environment. 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. The interoperability of systems and tools allow 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, many organizations still have areas working apart in silos. DM tools allow simultaneous engineering to be facilitated and optimized, preventing errors, anticipating corrections and creating nonlinear cascade effects. Meanwhile, regarding inter-organizational integration, DM systems are 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.

In answering the main research question, the role of DM in Industry 4.0 is to assist the development of production management models allowing end-to-end integration, a new work methodology that mitigates that business areas work in organizational silos and begin to work in a connected and integrated way, besides allowing more fast and accurate analyzes using reliable and updated data for more agile, contextualized, decentralized and dynamic decision-making.

5.1 Theoretical and empirical contributions

This section organizes the main contributions of the thesis according to the four main phases of the research design: theoretical mapping, critical success factors definition and framework development.

Theoretical Mapping

By developing a contextualized definition for digital manufacturing, it contributes theoretically to mitigating poor communication and misinterpretation when dealing with DM and other terminologies often used as synonyms. A clear definition empirically helps companies to accurately define the scope and non-scope of digital manufacturing projects, as well as align expectations by understanding their real purpose.

The study also contributes theoretically by proposing a framework considering the updated set of digital manufacturing tools and the Industry 4.0 technologies that can be explored together. It allows better understanding of the evolving DM application domain of digital manufacturing and its relation to the advanced manufacturing technologies. For practitioners this is important since presenting a clear and well-defined application domain is essential to create and plan DM adoption by defining the appropriate value package aligned to their strategic operations management. It will help organizations to select the tools and technologies that bring them greater competitive advantages while evolving in the development of new capabilities.

This new framework defining the current application domain, tools and Industry 4.0 technologies that are used in each manufacturing life cycle phase.

Critical Success Factors

By defining a set of critical factors and discuss them based on four different aspects this study assists companies showing which internal and external aspects directly influence the adoption of digital manufacturing in the context of industry 4.0.

It empirically shows that organizational aspects play a fundamental role in the success of the implementation. Understanding the differences between regular technologies adoption and DM adoption is also pivotal. What perhaps makes this type of project different from other implementation projects is the culture change that needs to occur behind it. It is not only about technology change, but also about radical changes throughout the manufacturing life cycle, directly interfering with how and when each activity could and should be done. Findings also identify technical factors that are unique to these organizations operating in Industry 4.0, such as those ones related to capturing and analyzing data in real time as well as end-to-end integration.

Framework development

The study contributes to the existing literature in investigating the new characteristics of DM in the context of Industry 4.0. It explored how these characteristics add value to processes and products, identifying necessary deliverables at each adoption stage. It also found how digital manufacturing technology changes affect operational and organizational strategies and conditions. In terms of managerial implications, the results support managers that seek to adopt DM. This also helps managers understand implementation dilemmas and empirically explores several difficulties encountered in various phases of the framework and proposes ways to mitigate them. Finally, it shows managers that when seeking greater organizational maturity in relation to the principles of Industry 4.0, they will be able effectively absorb added value of the various advanced manufacturing technologies. The social impact of the current study can be reflected in a more effective coordination of manufacturing lifecycle while assisting the continuous improvement of products and services both in terms of quality, time-to-market e mass customization.

The originality of this study is supported by the fact the SLR did not find any investigation that explored factors influencing DM in Industry 4.0, neither did any study proposing a comprehensive framework to assist companies in the path for DM adoption.

5.2 Limitations

The limitations are explored in three main aspects: theoretical, methodological and related to the practice.

Theoretical limitations are firstly related to scoping delimitation. The term most commonly used as a synonym of digital manufacturing is 'digital factory', but other terms such as ‘virtual manufacturing', 'smart factory' and 'smart manufacturing' are also incorrectly used as synonymous and it was not explored in a systematic way. Also, for the 'Application domain of digital manufacturing in Industry 4.0 framework' proposition, the framework proposed by Rüßmann et al. (2015) was used as base, although that does not cover all technologies that have emerged in recent years (e.g. artificial intelligence, blockchain, virtual reality). Thus, the work did not explore all possible technological relationships between DM tools and Industry 4.0 technologies.

Regarding methodological limitation, the survey did not use an equal number of professionals in the three categories consulted, presenting a higher number of researchers than manager and implementation consultants. However, this was mitigated by applying statistical significance tests. Second, although it was done intentionally, the lack of weights for factors is a limitation. This was intentionally done to better illustrate relevant factors, since explicit weights could lead to a discard of lower scored factors and depending on the company specific situation the weightings may vary. Third, during the case study the greatest limitation is related to the narrowness of the sample analyzed and sectors covered. Although few sectors have been explored, there are equally few sectors that use DM technology and the great majority of these companies are large multinationals. However, to capture boundaries of DM implementation, this should be expanded to other type of organizations, such as small and medium-sized enterprises (SME).

Related to the practice, the study does not extensively explore the trade-offs within the set of critical success factors, limiting it to only a few examples. In addition, it pointed to difficulties for horizontal integration of the value chain due to the lack of incentives for SMEs, but it also does not appropriate explore strategies creating incentives beyond financial returns.

5.3 Recommendations for future research

For future work, five gaps have been found and can be explored in-depth. First, few case studies have been conducted and few organizational sectors were explored. It is proposed to increase the number of cases and sectors so that critical success factors are stressed for comprehensive validation. In addition, no longitudinal study, which accompanies the entire DM implementation process using the framework was presented. Conducting this type of study will enable to analyze the results found in this study from another perspective, verifying if the implementation process behaves in a similar way to those presented by the experts who have a post-implementation view that may contain unidentified biases.

Second, it is proposed to expand the scope of research in the context of Industry 4.0. Future research may use the same process presented in this study to verify critical success factors for implementation and use of other Industry 4.0 technologies. Companies would benefit by understanding which critical factors already addressed could facilitate the implementation of those new technologies, while academically exploiting the unique features and requirements of each technology in Industry 4.0.

Third, it is important to define a set of capabilities and skills that organizations must develop for the use of each digital manufacturing tool, as well as specific capabilities for applying certain technologies. Focused on organizational capabilities, the study should focus in a life-cycle perspective to an integrated value chain and ecosystem approach towards digital transformation. Besides that, time length related to each phase in the framework and how organizational characteristic influences the temporal perspective can be explored.

Fourth, a tool that helps companies define which set of digital manufacturing tools will bring the greatest benefit based on their unique characteristics. Even companies in the same industry can get more value in using different tools, since their value proposition differs. In addition, pre-developed capabilities can facilitate the application of a specific set of tools, aiding in organizational learning and increasing the medium-term return. Also, it is recommended a continuous reviewing of available tools since suppliers are constantly presenting new advances and joint use of technologies.

Lastly, a gap that needs to be better explored is related to DM adoption by small and medium-sized enterprises. Despite DM system providing appropriate features for suppliers' integration and many large enterprises adopting it, there are few incentives for SMEs to adopt the technology due high complexity and cost. This creates a conflict of interest between large companies and their suppliers in the long run. To solve such conflicts, incentives must be created beyond short term financials, breaking the buyer-supplier paradigm and encouraging longer-term partnerships. Future work should explore new strategies to create such incentives and enabling horizontal integration.

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APPENDIX A – PAPERS

Paper 1

ANÁLISE DE ESTUDOS NA ÁREA DE MANUFATURA DIGITAL: UMA REVISÃO DA LITERATURA

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Resumo: *EMPRESAS EM BUSCA DE SE MANTEREM COMPETITIVAS E LÍDERES DE MERCADO TEM VISTO A NECESSIDADE DE INSERIR A MANUFATURA DIGITAL EM SUAS CORPORAÇÕES. A MANUFATURA DIGITAL BUSCA A INTEGRAÇÃO DOS MÉTODOS E FERRAMENTAS COMPUTER-AIDED PARA O PLANEJAMMENTO DE NOVOS PRODUTOS, PLANTAS PRODUTIVAS E PROCESSOS OPERACIONAIS, E DIVERSOS AUTORES JÁ ENFATIZAM OS BENEFÍCIOS DE SUA IMPLANTAÇÃO EM AMBIENTES FABRIS. ESTE ARTIGO TEM POR OBJETIVO COMPILAR OS AVANÇOS NAS PESQUISAS ACADÊMICAS REFERENTES À MANUFATURA/FÁBRICA DIGITAL, BUSCANDO ENTENDER A EVOLUÇÃO DAS PUBLICAÇÕES SOBRE O TEMA. OS RESULTADOS MOSTRARAM QUE DESDE O FINAL DA DÉCADA DE 90 HÁ UM CRESCENTE INTERESSE PELA ÁREA E UM AUMENTO SIGNIFICATIVO DO NÚMERO DE PUBLICAÇÕES. PAÍSES COMO ALEMANHA, ESTADOS UNIDOS E CHINA, ALÉM DE PIONEIROS, SÃO OS QUE MAIS CONTRIBUEM PARA O TEMA, PRINCIPALMENTE DOS DEPARTAMENTOS DE ENGENHARIA DE PRODUÇÃO E MECÂNICA, PORÉM, AINDA NÃO HÁ UM GRUPO DEFINIDO DE AUTORES QUE SE DESTAQUE. TAMBÉM FOI POSSÍVEL IDENTIFICAR QUE TERMOS COMO SISTEMAS, MODELOS, INTEGRAÇÃO, SIMULAÇÃO, PLANEJAMENTO E PRODUÇÃO SÃO COMUMENTE UTILIZADOS NO CONTEXTO DA MANUFATURA DIGITAL. ESSE TRABALHO CONTRIBUIU NO CENÁRIO ACADÊMICO E INDUSTRIAL AO POSSIBILITAR UM MELHOR DIRECIONAMENTO DAS PESQUISAS E BUSCAS DE INFORMAÇÕES SOBRE O TEMA.*

Palavras-chaves: *MANUFATURA DIGITAL; FÁBRICA DIGITAL; SISTEMAS COMPUTER-AIDED; SIMULAÇÃO*

Área: *1 - GESTÃO DA PRODUÇÃO*
Sub-Área: *1.6 - SIMULAÇÃO DA PRODUÇÃO*

ANALYSIS OF STUDIES ON DIGITAL MANUFACTURING: A LITERATURE REVIEW

Abstract: *COMPANIES SEEKING TO REMAIN COMPETITIVE AND MARKET LEADERS HAVE SEEN THE NECESSITY TO INSERT THE DIGITAL MANUFACTURING IN THEIR COMPANIES. DIGITAL MANUFACTURING SEEKS TO INTEGRATE METHODS AND COMPUTER-AIDED TOOLS (CA) TO PLAN NEW PRODUCTS, PLANTS AND OPERATIONAL PROCESSES, AND SEVERAL AUTHORS HAVE EMPHASIZED THE BENEFITS OF ITS IMPLEMENTATION IN MANUFACTURING ENVIRONMENT. THIS PAPER AIMS TO COMPILE THE ADVANCES IN ACADEMIC RESEARCH RELATED TO DIGITAL MANUFACTURING/FACTORY, SEEKING TO UNDERSTAND THE EVOLUTION OF PUBLICATIONS ON THIS SUBJECT. THE RESULTS SHOWED THAT SINCE THE LATE 90´S THERE IS A GROWING INTEREST IN THIS THEME AND SIGNIFICANT INCREASE IN THE NUMBER OF PUBLICATIONS. COUNTRIES LIKE GERMANY, USA AND CHINA, BESIDES BEING PIONEERS, ARE THE MAIN CONTRIBUTORS TO THE THEME, MAINLY IN MECHANICAL AND INDUSTRIAL ENGINEERING DEPARTMENTS, HOWEVER, THERE IS STILL NO DEFINED GROUP OF AUTHORS WHO STAND OUT. IT WAS ALSO FOUND THAT TERMS LIKE SYSTEMS, MODELS, INTEGRATION, SIMULATION, PLANNING AND PRODUCTION ARE OFTEN USED IN THE CONTEXT OF DIGITAL MANUFACTURING. THIS STUDY CONTRIBUTES TO ACADEMIC AND INDUSTRIAL SCENARIO DRIVING FUTURE RESEARCHES ABOUT THIS THEME.*

Keyword: *DIGITAL MANUFACTURING; DIGITAL FACTORY; COMPUTER-AIDED SYSTEMS, SIMULATION*

1. Introdução

A manufatura digital vem evoluindo ao longo das últimas duas décadas, acompanhando os avanços nas tecnologias de informação e comunicação. Para Kühn (2006), a manufatura digital centra-se na integração computacional de técnicas e ferramentas disponíveis em diferentes níveis de planejamento, possibilitando interconectar, desenvolver interfaces e integrar os processos de produção e controle. Bracht e Masurat (2005) destacam que esta integração pode ser representada por uma única base de dados na forma de *Computer-Aided Systems* (CA) que criam uma plataforma para o planejamento de novos produtos, plantas produtivas e operações produtivas.

Freedman (1999) já destacava no inicio das aplicações da manufatura digital que seria possível verificar dinamicamente a interferência que ocorre entre as peças e ferramentas, componentes e equipamentos, equipamentos e pessoas dentre outros artefatos. Também é possível verificar que, por meio do uso desse tipo de tecnologia, a implementação de novos projetos pode obter melhores resultados da primeira vez. Embora a construção do protótipo "virtual" possa requisitar maior tempo de desenvolvimento, o benefício resultante pode ser visto posteriormente por meio da descoberta de problemas e introdução das correções sem a necessidade da produção, reduzindo a poucas horas testes que em média demandam semanas. Tais reduções em termos de custo e tempo também são apresentadas por outros autores (PAVANI, 2007; FREITAS, 2010; MOREIRA, 2011).

No entanto, observa-se que as pesquisas relacionadas à manufatura digital não são proporcionais aos seus benefícios. A maioria dos temas de pesquisa dentro das disciplinas acadêmicas possuem análises de produtividade de pesquisa em termos de autores, instituições e outras características bibliométricas (HSIEH, 2009) e não são encontrados trabalhos de revisão de literatura que caracterizam o tema manufatura digital.

Este estudo tem por objetivo compilar os avanços nas pesquisas acadêmicas referentes à manufatura/fábrica digital, buscando entender a evolução das publicações, autores e periódicos/conferências mais relevantes, e as áreas que mais contribuem para evolução do tema.

O artigo apresenta primeiramente uma revisão bibliográfica no tema manufatura digital, compilando conceitos e identificando as suas principais características; nas seções subsequentes são apresentados os procedimentos metodológicos, os resultados da revisão de literatura e a sua discussão, que se caracterizaram pelo conteúdo das publicações levantadas; para finalmente, nas considerações finais apresentar as contribuições do trabalho para a academia e para as empresas, além de sugestões para pesquisas futuras.

2. Manufatura digital

No início da década de 90, pesquisadores começaram a perceber mudanças nos rumos dos processos de simulação das indústrias. De acordo com Freedman (1999), empresas passavam da "engenharia tradicional", na qual a concepção de um produto demandava inúmeras revisões e protótipos, além de ser consideravelmente onerosos, para um conceito de "tecnologias de manufatura digital integrada", no qual softwares de simulação sofisticados permitiam, por exemplo, promover cerca de 70% das melhorias antes da concepção do protótipo resultando em economias enormes e um *time to market* muito mais rápido.

O conceito de manufatura digital (também chamada de fábrica digital) é definido por inúmeros autores. Kühn (2006) em sua definição clássica entende a fábrica digital como sendo a integração de métodos e ferramentas disponíveis para avaliar e planejar o produto e respectivamente controlar a produção e fazer o planejamento da fábrica.

De acordo com Curran et al. (2007) as fábricas digitais servem para: (1) simulação e planejamento do conceito inicial; (2) planejamento do conceito final e otimização de rede; (3) planejamento detalhado e verificação em sistemas 3-D CAD; (4) detecção de conflitos e gestão de mudança.

Ainda segundo Kühn (2008) a fábrica digital integra produtos, processos e realiza modelagem para uma visualização avançada e simulação da fábrica, com objetivo de promover melhoria de qualidade e dinamismo dos produtos e processos.

Nas últimas décadas, os sistemas de manufatura digital foram focados no design estático dos produtos, mais atualmente, o estado da arte concentra-se na modelagem e simulação de plantas industriais dinâmicas. Sistemas de maquete digital analisam o ciclo do processo de produção, a ergonomia dos trabalhadores, a localização e o desempenho das máquinas, e as etapas de montagem (DUARTE FILHO, et al., 2010).

Na visão de Fang-ying (2010) fábrica digital é entendida ainda, como um ambiente de computador integrado, que visa alcançar uma verdadeira integração dos sistemas CAD / CAPE / CAM. De acordo com Shariatzadeh (2012) ela viabiliza o ambiente virtual para o projeto do ciclo de vida de processos de fabricação e sistemas de manufatura utilizando simulação e tecnologias de realidade virtual para otimizar o desempenho, a produtividade, o tempo, custos e ergonomia.

Mais recentemente a manufatura digital é definida por Roy et al. (2014), como uma abordagem integrada para melhoria na engenharia de processos de produto e produção, que tipicamente interconecta diferentes componentes-chave, como simulação (simulação continua ou de eventos discretos), otimização, análise de dados, realidade virtual em 3D, gerenciamento de dados e gerenciamento de fluxo de trabalho. Para tal usa modelos 3D na visualização, modelagem e simulação do processo de produção e do sistema de produção buscando efetividade e produtividade para a linha de produção dentro das limitações de recursos impostas. Além disso, o uso estendido de simulação baseada em fábrica digitais permite projetar, analisar e prever os futuros comportamentos dos sistemas de produção que estão sendo concebidos.

Segundo Al-Zaher (2014), a tecnologia de manufatura digital é usada para facilitar a colaboração entre design de produto e funções de engenharia de fabricação, fornecendo aos engenheiros de fabricação visibilidade antecipada dos dados de design de produto. Além disso, é uma forma de avaliar o impacto de determinadas mudanças no projeto no processo de fabricação, identificar possíveis problemas e recomendar melhorias para o produto.

A Tabela 1 apresenta uma compilação cronológica dos conceitos da manufatura digital.

TABELA 1 - Definições de manufatura/fábrica digital.

Ano	Autor (es)	Definição de manufatura/fábrica digital
2006	Kühn	Integração de métodos e ferramentas disponíveis para avaliar e planejar o produto e respectivamente controlar a produção e fazer o planejamento da fábrica.
2007	Curran et al.	(i) simulação e planejamento conceitual inicial; (ii) planejamento conceitual final e otimização de rede; (iii) planejamento detalhado e verificação 3-D CAD; (iv) detecção de conflitos e gestão de mudança.
2008	Kühn	Integra produtos, processos e realiza modelagem para uma visualização avançada e simulação da fábrica.
2010	Duarte Filho	Modelagem e simulação de plantas industriais mais dinâmicas.
2010	Fang-ying	Ambiente de computador integrado, que visa alcançar uma verdadeira integração dos sistemas CAD / CAPE / CAM.
2012	Shariatzadeh	Viabiliza o ambiente virtual para o projeto do ciclo de vida de processos de fabricação e sistemas de manufatura utilizando simulação e tecnologias de realidade virtual para otimizar o desempenho, a produtividade, o tempo, custos e ergonomia.
2014	Roy	Abordagem integrada para melhoria na engenharia de processos de produto e produção, que tipicamente interconecta diferentes componentes-chave, como simulação (simulação continua ou de eventos discretos), otimização, análise de dados, realidade virtual em 3D, gerenciamento de dados e gerenciamento de fluxo de trabalho.

A partir dos conceitos apresentados é possível analisar as vantagens ao aplicar a manufatura digital nas empresas.

2.1 Benefícios da manufatura digital

Diversos autores reconhecem os benefícios do uso da manufatura digital em ambientes fabris e esse tipo de tecnologia é utilizado principalmente nos setores automotivo, aeroespacial e *offshore*. Na Tabela 2 são apresentados alguns desses benefícios.

TABELA 2 - Benefícios do uso da manufatura digital.

Ano	Autor(es)	Benefícios do uso da manufatura digital
2000	Brown	Maior confiabilidade no processo de estimativa de custo de projetos grandes e de longo prazo.
2000	Worn	Problemas são detectados precocemente, proporcionando tempos reduzidos para ajustes nos processos.
2000	Worn	Resultados de simulações virtuais podem ser facilmente aplicados a problemas reais utilizando interfaces bem definidas.
2000	Brown	Uso de simulação para comunicação das inovações aos clientes, gerando maior confiabilidade e influência na decisão.
2005	Zuelch e Stowasser	Todos os aspectos de uma fábrica podem ser desenvolvidos e aperfeiçoados desde a concepção até a fabricação física de um produto, cumprindo as metas em relação à qualidade, tempo e custo.
2005	Zuelch e Stowasser	Uma vez que o produto digital passa com sucesso pela fábrica digital, ele é liberado para fabricação na fábrica real com custos reduzidos de forma representativa.
2013	Dombrowski e Ernst	Permite a comunicação entre engenheiros de projeto e outros stakeholders no processo de design ao utilizar terminologias e linguagem similares.
2013	Dombrowski e Ernst	De acordo com estudos de caso, o uso da manufatura digital permite redução de até 30% de tempo para introdução de novos produtos no mercado e redução, em média, de 15% nos custos relacionados à alterações de projetos e processos. Além disso, permite, em média, 5% de economia na escolha de equipamentos por proporcionar maior maturidade no conhecimento das mesmas.
2013	Dombrowski e Ernst	Possibilidade de simular e analisar sistemas fisicamente não existentes ou já existentes, sem qualquer perturbação das operações.
2013	Dombrowski e Ernst	Possibilidade de comparar diferentes cenários de um sistema e analisar o comportamento deles no longo prazo, pensando simultaneamente em fluxo e ferramentas.
2014	Al-Zaher	Facilidade na colaboração entre design de produto e funções de engenharia de fabricação, fornecendo aos engenheiros de fabricação uma visibilidade antecipada dos dados de design de produto.
2014	Al-Zaher	Possibilidade de avaliação do impacto de uma determinada mudança no projeto do processo de fabricação, identificando possíveis problemas e recomendando melhorias para o produto.
2014	Sivard et al.	Promove a interoperabilidade das ferramentas de engenharia por meio do fornecimento de uma terminologia comum e modelo de informação utilizada para descrever tarefas típicas.

Nesse contexto é percebida a importância da manufatura digital na engenharia de produto, processo e produção.

3. Metodologia

Como estratégia de pesquisa, este estudo realiza uma revisão de literatura sobre manufatura digital. A revisão da literatura visa demonstrar o estágio atual da contribuição acadêmica em torno de um determinado assunto. Ela proporciona uma visão abrangente de pesquisas e contribuições anteriores, conduzindo ao ponto necessário para investigações futuras e desenvolvimento de estudos posteriores (ALVES, 1992).

O desenvolvimento de um estudo específico é observado por meio das produções científicas atribuídas a ele. Atualmente é possível realizar análises de artigos em amplas categorias como autores, título, ano, citação, palavras chave, entre outros termos diretamente relacionado com extensão de conhecimento, por meio de análise bibliométrica de dados. O uso da análise bibliométrica permite a avaliação da contribuição literária em cenários específicos (MCINTIRE, 2006; LEIDESDORFF, 2007). Esta pesquisa utiliza como técnica a análise bibliométrica na medida em que busca estudar as características das publicações sobre manufatura digital e define números para a produção científica no tema.

Os artigos obtidos como resultado foram tratados também por meio da técnica de análise de conteúdo, como uma forma de compilar os conceitos identificados. Este tipo de análise é definida como um conjunto de técnicas de análise de comunicações que utiliza procedimentos sistemáticos e objetivos de descrição do conteúdo das mensagens, permitindo a inferência de conhecimentos relativos às variáveis identificadas nessas mensagens (BARDIN, 1994).

3. 1 Procedimentos metodológicos

Este estudo apresenta um *framework* de condução da pesquisa (Figura 1FIGURA 1) que visa encontrar um conjunto de artigos referentes à manufatura digital. O *framework* possui cinco fases macro: (i) definição do tema; (ii) definição dos temos de busca; (iii) definição das bases; (iv) estudo bibliométrico (compilação de dados); e (v) análise de conteúdo.

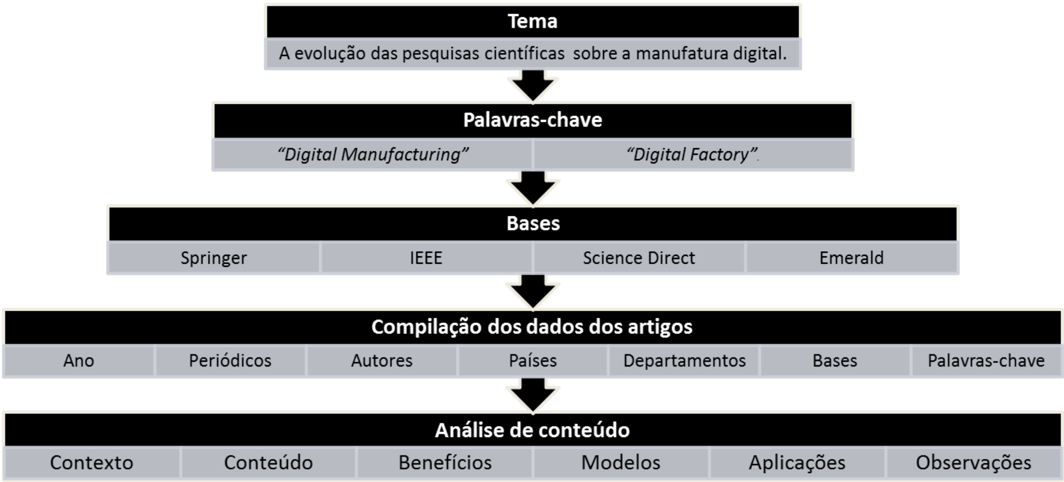

FIGURA 1 - *Framework* de condução da pesquisa.

Seguindo o *framework*, foram utilizados os termos de busca "*digital manufacturing*" e "*digital factory*" nas bases Springer, IEEE, Science Direct e Emerald. Tais termos deveriam obrigatoriamente aparecer no título ou nas palavras-chave dos artigos encontrados. Desta primeira busca resultaram 112 artigos, dos quais foram extraídas as informações: ano, periódico, autores, países, departamentos, base e palavras-chave. A partir da compilação dos dados o portfólio de trabalho foi reduzido para 91 artigos, pois foram excluídos editoriais e documentos com duplicidade de palavras-chave.

A etapa posterior da pesquisa foi a análise do conteúdo dos artigos, na qual foram extraídas, quando possível, informações como: contexto, definição, benefícios, modelos, aplicações, observações. Estes dados auxiliaram na construção do referencial teórico.

4. Resultados

Por meio da análise dos dados compilados foram identificados cinco aspectos das publicações relacionadas à manufatura digital: (i) a evolução das publicações (Figura 2); (ii) os principais periódicos e conferências (Tabela 3); (iii) as áreas e departamentos que estão estudando a manufatura digital (Tabela 4); (iv) os países onde se estuda a manufatura digital (Figura 3); (v) termos relacionados com a manufatura digital (Figura 4).

É válido ressaltar que os autores das publicações também foram estudados, porém, nenhum autor apresentou três ou mais artigos. Assim, constata-se uma diversidade de autores abordando a manufatura digital. Além disso, foi percebida uma concentração significativa de artigos nas bases Science Direct e IEEE, somando 84% da totalidade dos artigos coletados.

Considerando as bases utilizadas para o desenvolvimento deste estudo, os primeiros artigos relacionados à manufatura digital originaram-se em 1999. Embora haja variações na quantidade de publicações no decorrer dos anos, identifica-se uma tendência crescente, conforme apresentado na Figura 2.

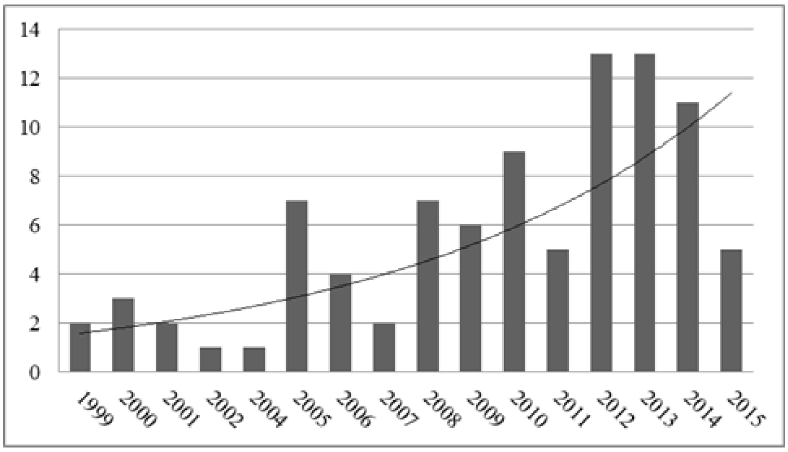

FIGURA 2 – Evolução das publicações relacionadas à manufatura digital.

O conjunto de artigos selecionados possui diferentes abordagens da manufatura digital, tais como modelos de implementação, modelos conceituais, comparação da engenharia convencional e manufatura digital e estudos de casos. Os periódicos e as conferências mais significativos no contexto da manufatura digital estão citados na Tabela 3.

TABELA 3 - Principais periódicos e conferências no contexto da manufatura digital.

Publicações por periódicos/conferências no período 1999-2015	**Porcentagem**
Procedia CIRP	13,2%
Computers in Industry	5,5%
Winter Simulation Conference	4,4%
Procedia Engineering	4,4%
CIRP Annals - Manufacturing Technology	4,4%

The International Journal on Interactive Design and Manufacturing	3,3%
The International Journal of Advanced Manufacturing Technology	3,3%
Outros	=< 3%

A manufatura digital é tema de estudo em diferentes departamentos, destacando-se na Engenharia de Produção e Mecânica, conforme pode ser visto na Tabela 4.

TABELA 4 - Principais departamentos no contexto da manufatura digital.

Publicações por departamento no período 1999-2015	**Porcentagem**
Engenharia Industrial	17,6%
Engenharia Mecânica	15,4%
Engenharia Elétrica	4,4%
Ciência e Gestão	4,4%
Sistemas de Manufatura	4,4%
Sistemas de informação	3,3%
Tecnologia de Manufatura Integrada	3,3%
Engenharia Aeroespacial	3,3%
Engenharia Mecatrônica	3,3%
Outros	=< 3%

Embora o fato da área da Robótica ser uma das primeiras áreas a publicar sobre o tema juntamente com a Engenharia Industrial, ela não apresentou quantidade de artigos superior a 3,3% do total. Os departamentos que não foram pioneiros, porém apresentaram porcentagens significativas de publicações a partir de 2005, foram as áreas de Engenharia Mecânica, Engenharia Elétrica, Administração, Tecnologia da Manufatura Integrada, Engenharia Aeroespacial e Engenharia Mecânica. Após 2010, os departamentos de Sistemas de Manufatura e Sistemas da Informação também apresentaram quantidades relevantes de estudos. Assim, nota-se uma crescente diversificação dos departamentos preocupados em estudar o tema ao decorrer dos anos.

A Figura 3 apresenta os países mais representativos nas publicações sobre manufatura digital. Alemanha, Estados Unidos e China juntos apresentam mais de 50% das publicações.

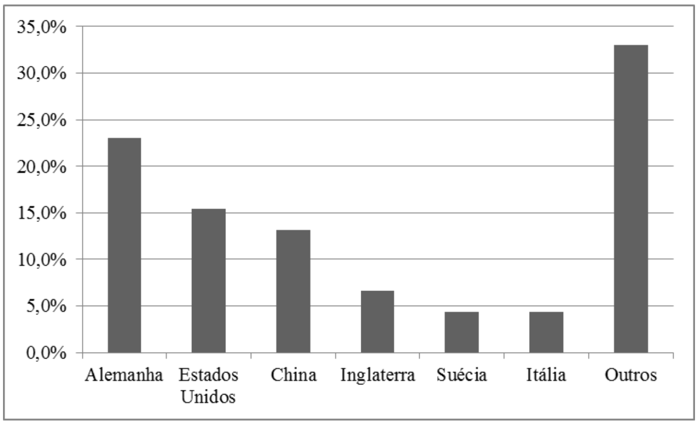

FIGURA 3 – Principais países abordando a manufatura digital.

Cada país possui departamentos específicos abordando a manufatura digital. Na Alemanha os estudos estão concentrados principalmente nos departamentos de Engenharia Industrial e Sistemas de Manufatura. Já nos Estados Unidos muitas publicações são provenientes da Engenharia Elétrica e Mecânica. As pesquisas conduzidas na China encontram-se nas áreas de Tecnologia da Manufatura Integrada e de Engenharia Mecânica.

O cruzamento dos dados de origem e período das publicações referentes à manufatura digital possibilitou a análise dos países pioneiros. Entre 1999 e 2004 a Alemanha e os Estados Unidos da América foram os principais países a apresentarem estudos sobre o assunto. Já no período de 2005 e 2011 nota-se uma forte concentração de publicações de pesquisadores da China, Alemanha e Inglaterra. Por fim, entre 2011 e 2015 os Estados Unidos, Alemanha e Itália se destacam neste contexto.

Tendo em vista que as palavras-chaves das publicações gerou uma lista diversificada, na qual não se obteve muitas repetições de termos, foram analisados os assuntos mais citados nos títulos das publicações para agrupar as palavras-chaves. Para isso, foi utilizada a ferramenta Atlas.TI® para auxiliar na contagem da frequência das palavras contidas nos títulos dos artigos. A Figura 4 apresenta os assuntos abordados nas palavras-chaves e títulos.

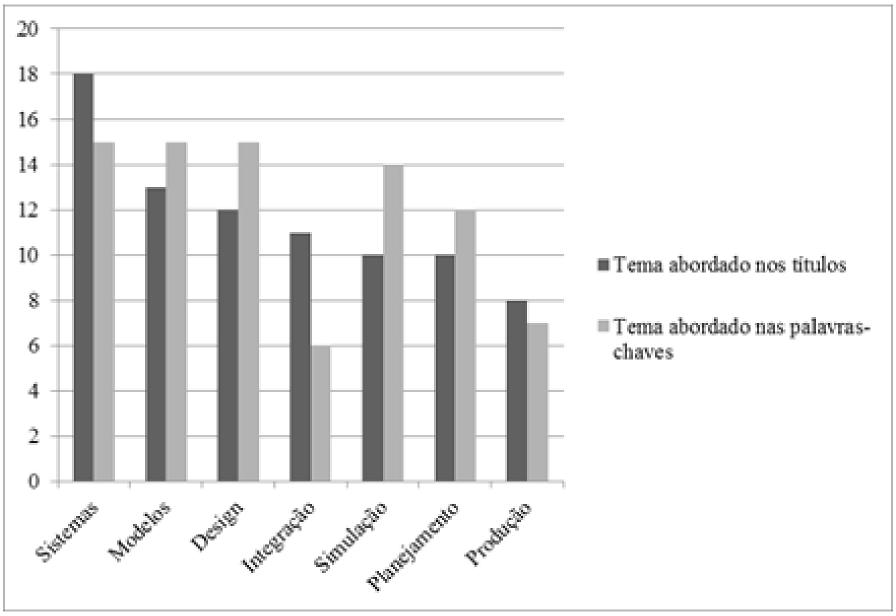

FIGURA 4 – Temas abordados junto com a manufatura digital.

As palavras mais representativas quantitativamente dos títulos e palavras-chaves - Sistemas e Modelos – estão relacionadas à diferentes temas e não foi constada uma forte concentração em um assunto específico.

Uma das funcionalidades da manufatura digital é possibilitar a simulação de um processo/produto existente ou encontrar possíveis melhorias, diminuindo a quantidade de protótipos e evitando possíveis erros futuros. Para Rooks (1999) a tecnologia da manufatura digital permite a integração da simulação (ferramenta de validação) e planejamento e controle de produção, tais como programação de produção e ERP. Kühn (2006) apresenta que a manufatura digital permite a aplicação de diferentes tipos de simulação, como a simulação de eventos discretos e simulação de movimentos 3D, melhorando o planejamento do processo e produto em todos os níveis e permitindo um controle integrado desde o planejamento até o chão de fábrica.

Neste contexto, Zulch e Grieger (2005) salientam que o planejamento encontra-se presente na totalidade do ciclo de vida do produto e sua respectiva produção e a integração das áreas de desenvolvimento de produto e de projeto de fábrica possibilita uma operação em harmonia e assim, a redução do tempo entre o lançamento dos novos produtos. O suporte para o planejamento de processo e de produto é dado pela manufatura digital por meio de várias ferramentas, tais como programas de modelagem em 3D e simulações.

A presença significativa do tema produção reforça a aplicação da manufatura digital nos processos produtivos. Yang et al. (2008) dividem a manufatura digital em sete áreas: (i) gestão da qualidade. (ii) planejamento virtual da montagem, (iii) simulação da produção atual; (iv) layout da planta; (v) engenharia homem-máquina; (vi) planejamento de processo; (vii) validação da capacidade produtiva. Assim, integra os processos de desenvolvimento, teste e otimização do produto; desenvolvimento e otimização do processo produtivo; design e melhoria da planta; e planejamento e controle de produção. (KÜHN, 2006)

Segundo Petzelt et al. (2010), O tema Integração é relevante no contexto da manufatura digital, embora não apresente muitas citações nas palavras-chaves. A preocupação da integração de novas ferramentas digitais está aumentando conforme o aparecimento de novas tecnologias. A implementação da manufatura digital envolve muitas áreas e ferramentas exigindo assim uma forte integração, seja das ferramentas *Computer-Aided* ou dos diferentes departamentos que impactem no projeto.

O tema design mostra-se significativo nos dois contextos procurados. As ferramentas e métodos da manufatura digital podem ser utilizados em diferentes atividades de design, como por exemplo, as simulações feitas por diferentes agentes envolvidos no trabalho colaborativo (STEF et al., 2013). Ao facilitar a integração entre o design e a engenharia de manufatura, a manufatura digital permite uma visão antecipada dos dados de design do produto final (AL-ZAHER e ELMARAGHY, 2014). A manufatura digital também está inserida no contexto de design do layout de fábrica, na qual pode facilitar e dar suporte no seu desenvolvimento (SHARIATZADEH et al., 2012).

Foram constatadas algumas concentrações do foco do estudo por país. As publicações provenientes da Alemanha e da China estão fortemente relacionadas com os temas de Planejamento e Simulação, enquanto os estudos abordando Design estão concentrados na Inglaterra. Já os Estados Unidos apresentaram diversidades nos temas, porém foi constatado que a maioria dos estudos da manufatura digital com ênfase na impressão 3D é de origem desse país.

5. Conclusão

Frente a um mercado competitivo, as empresas precisam de alguma forma estar fortes, preparadas para as adversidades e também estar sempre à frente da concorrência. Entende-se que a manufatura digital auxilia as empresas a entrar de maneira mais rápida no mercado e também diminuir consideravelmente os custos na condução de um projeto. Diante desse fato as contribuições mais importantes deste artigo para as organzações se dão quando são apresentadas a definição e características da manufatura digital, além de mostrar seus benefícios. Por exemplo, a manufatura digital traz benefícios na integração entre design, planejamento, simulação e produção, além de proporcionar melhorias nos modelos e sistemas das empresas.

O artigo também contribui para a academia ao apresentar bases, periódicos e conferências que se destacam pela quantidade de publicação no tema, os países e departamentos que mais contribuem, além de identificar os assuntos que estão sendo abordados no contexto da manufatura digital. Além disso, identifica vários conceitos de manufatura digital defendidos por diferentes autores, possibilitando o direcionamento de estudos futuros. Por exemplo, quando um pesquisador inicia uma pesquisa sobre manufatura digital ele pode focar na base Science Direct por apresentar um grande número de artigos no tema, bem como escolher os periódicos que apresentam maior número de artigos.

Os resultados obtidos neste estudo apresentam algumas limitações: (i) o termo de busca está restrito à "*digital manufacturing*" e "*digital factory*"; (ii) as bases utilizadas para a busca de artigos.

Como possíveis trabalhos futuros, sugere-se a inserção dos termos "*virtual manufacturing*" e "*virtual factory*", uma vez que foi constatado o uso desses termos como sinônimos da manufatura/fábrica digital por diferentes autores, e a análise de modelos conceituais e de implementação contidos no portfolio de trabalho estabelecido.

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Paper 2

Reviewing Digital Manufacturing concept in the Industry 4.0 paradigm

E. H. D. Ribeiro da Silva, A. C. Shinohara, E. Pinheiro de Lima and J. Angelis

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 and applications 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.**

I. 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 [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 manufacturing industry [8], [9]. Manufacturing becoming increasingly multidisciplinary was perhaps inevitable. From the combination of organizational sciences, such as Total Quality Management - TQM, Just in Time – JIT, Concurrent Engineering and Lean Manufacturing; with engineering science of CIM emerged the concept of digital manufacturing that highlighted the need for more collaborative product and process design [9], [10].

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 explores the concept 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.

II. 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 [11], to compile the identified concepts. The software Atlas TI® was used to conduct the analysis.

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In a recent literature review on Digital Manufacturing, Shinohara et al. [12] 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 [13] 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 [14]. Fig. 1 illustrates the search strategy using the PRISMA diagram flow[15].

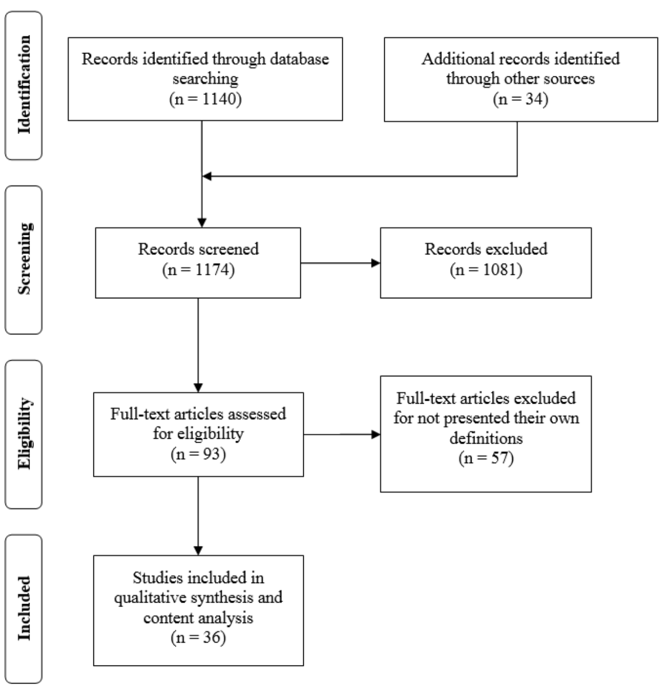

Figure 1. Search strategy and studies selection (PRISMA flow diagram)

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.

III. RESULS

The results of the systematic literature review are analyzed to answer the research question. 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.

TABELA I
MOST USED TERMS TO DEFINE DIGITAL FACTORY

Term	**Author(s) using term**
PPR (Product, Process and/or Resources)	Wenzel, Jessen, and Bernhard 2005 [16]; Zülch and Grieger 2005 [17]; Bracht and Masurat 2005 [18]; Kuehn 2006 [19]; Pakkala and Lopez 2006 [20]; Ŝtefánik et al. 2008 [21]; Zhao et al. 2009 [22]; Kjellberg et al. 2009 [23]; Gregor et al. 2009 [24]; Cheutet et al. 2010 [25]; Azevedo and Almeida 2011 [26]; Polášek, Bureš, and Šimon 2015 [27].
Digital model	Wiendahl, Harms, and Fiebig 2003 [28]; Wenzel, Jessen, and Bernhard 2005 [16]; Zülch and Grieger 2005 [17]; Bracht and Masurat 2005 [18]; Ŝtefánik et al. 2008 [21]; Kjellberg et al. 2009 [23]; Gregor and Medvecký 2010 [29]; Cheutet et al. 2010 [25]; Azevedo and Almeida 2011 [26]; Malak and Aurich 2013 [30]; Shariatzadeh et al. 2016 [31].
Support	Wenzel, Jessen, and Bernhard 2005 [16]; Zülch and Grieger 2005 [17]; Kuehn 2006 [19]; Butala et al. 2008 [32]; Gregor and Medvecký 2010 [29]; Zuehlke 2010 [33]; Cheutet et al. 2010 [25]; M. Matsuda, Kashiwase, and Sudo 2012 [34]; Constantinescu et al. 2014 [35]; Polášek, Bureš, and Šimon 2015 [27].
Simulation	Wiendahl, Harms, and Fiebig 2003 [28]; Pakkala and Lopez 2006 [20]; Zhao et al. 2009 [22]; Gregor and Medvecký 2010 [29]; Zuehlke 2010 [33]; Cheutet et al. 2010 [25]; Azevedo and Almeida 2011 [26]; M. Matsuda, Kashiwase, and Sudo 2012 [34]; Dombrowski and Ernst 2013 [36]; Matsuda et al. 2016 [37].
Tools	Wenzel, Jessen, and Bernhard 2005 [16]; Zülch and Grieger 2005 [17]; Kjellberg et al. 2009 [23]; Zuehlke 2010 [33]; Cheutet et al. 2010 [25]; Azevedo and Almeida 2011 [26]; Malak and Aurich 2013 [30]; Constantinescu et al. 2014 [35]; Polášek, Bureš, and Šimon 2015 [27].
Production planning	Zülch and Grieger 2005 [17]; Bracht and Masurat 2005 [18]; Kuehn 2006 [19]; Pakkala and Lopez 2006 [20]; Ŝtefánik et al. 2008 [21]; Gregor et al. 2009 [24]; Polášek, Bureš, and Šimon 2015 [27]; Matsuda et al. 2016 [37].
Integration	Kuehn 2006 [19]; Ŝtefánik et al. 2008 [21]; Zhao et al. 2009 [22]; Gregor et al. 2009 [24]; Gregor and Medvecký 2010 [29]; Zuehlke 2010 [33]; Azevedo and Almeida 2011 [26].
Design	Kuehn 2006 [19]; Ŝtefánik et al. 2008 [21]; Butala et al. 2008 [32]; Zhao et al. 2009 [22]; Cheutet et al. 2010

	[25]; Azevedo and Almeida 2011 [26]; Shariatzadeh et al. 2016 [31].
Production system	Bracht and Masurat 2005 [18]; Kjellberg et al. 2009 [23]; Gregor and Medvecký 2010 [29]; Zuehlke 2010 [33]; M. Matsuda, Kashiwase, and Sudo 2012 [34]; Shariatzadeh et al. 2016 [31].
Data	Westkämper and von Briel 2001 [38]; Ŝtefánik et al. 2008 [21]; Gregor et al. 2009 [24]; Azevedo and Almeida 2011 [26].
Factory planning	Wenzel, Jessen, and Bernhard 2005 [16]; Zuehlke 2010 [33]; Constantinescu et al. 2014 [35].
ERP	Ŝtefánik et al. 2008 [21]; Gregor et al. 2009 [24]; Zuehlke 2010 [33].

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.

TABELA II
MOST USED TERMS TO DEFINE DIGITAL MANUFACTURING

Term	Author(s) using term
PPR (Product, Process and Resources)	Maropoulos 2003 [39]; Curran et al. 2007 [40]; Butterfield et al. 2007 [41]; Nylund, Salminen, and Andersson 2007 [42]; Filho et al. 2009 [43]; Chryssolouris et al. 2009 [44]; Coze et al. 2009 [8]; Menéndez et al. 2012 [45]; Al-Zaher and ElMaraghy 2014 [46].
Data	Maropoulos 2003 [39]; Curran et al. 2007 [40]; Mahesh et al. 2007 [47]; Butterfield et al. 2007 [41]; Filho et al. 2009 [43]; Al-Zaher and ElMaraghy 2014 [46].
Production planning	Butterfield et al. 2007 [41]; Chryssolouris et al. 2009 [44]; Coze et al. 2009 [8]; Lee, Han, and Yang 2011 [48]; Lee et al. 2016 [49].
Simulation	Butterfield et al. 2007 [41]; Filho et al. 2009 [43]; Coze et al. 2009 [8]; Menéndez et al. 2012 [45]; Al-Zaher and ElMaraghy 2014 [46].
Design	Nylund, Salminen, and Andersson 2007 [42]; Butterfield et al. 2007 [41]; Coze et al. 2009 [8]; Menéndez et al. 2012 [45]; Al-Zaher and ElMaraghy 2014 [46].
Tools	Westkämper 2007 [50]; Nylund, Salminen, and Andersson 2007 [42]; Filho et al. 2009 [43]; Coze et al. 2009 [8]; Lee, Han, and Yang 2011 [48]; Menéndez et al. 2012 [45].
PLM/PDM	Maropoulos 2003 [39]; Curran et al. 2007 [40]; Filho et al. 2009 [43]; Chryssolouris et al. 2009 [44]; Menéndez et al. 2012 [45].
Integration	Curran et al. 2007 [40]; Butterfield et al. 2007 [41]; Nylund, Salminen, and Andersson 2007 [42]; Lee, Han, and Yang 2011 [48].
Information management	Maropoulos 2003 [39]; Curran et al. 2007 [40]; Butterfield et al. 2007 [41]; Filho et al. 2009 [43].
Integrated environment	Butterfield et al. 2007 [41]; Filho et al. 2009 [43]; Coze et al. 2009 [8].
Validation	Chryssolouris et al. 2009 [44]; Coze et al. 2009 [8].

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.

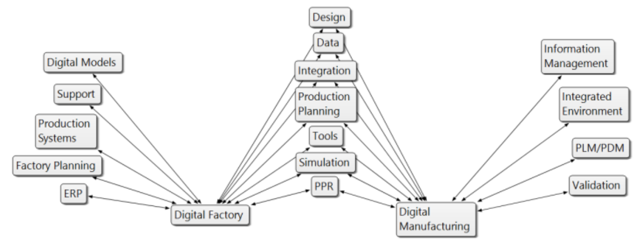

Figure 2. Content analysis result

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 present in the object which 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.

IV. DISCUSSION

This study sought to identify how digital manufacturing is defined considering the new paradigm of Industry 4.0. In 2005, Dalton-Taggart [51] 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 [52], 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 [39]–[41], [47]. 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 conducted 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 [17], [28], [30], [31], [38]. 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. It is concerned with the representation of the product and process in a digital way, but also 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 [53].

DM is 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.

TABELA II
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 first 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.

V. 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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Paper 3

The International Journal of Advanced Manufacturing Technology

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

--Manuscript Draft--

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Abstract:	Digitalization of manufacturing is on the industry application research agenda, as technologies of the internet of things are becoming available and adopted in large scale by many industries. This study analyzes the application domain of Digital Manufacturing while considering the new industrial paradigm. Based on the content analysis, joint applications of digital manufacturing 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 to a better understanding of the future challenges that academia and companies face by positioning digital manufacturing conceptually and delimiting its application domain.

Dear Professor Pilati,

We are submitting our paper “Operating Digital Manufacturing in Industry 4.0: the role of advanced manufacturing technologies” to be considered for the Special Issue “Design and management of Digital Manufacturing & Assembly Systems in the Industry 4.0 era”.

On the three questions regarding (1) main contribution to the field, (2) what is novel in theory and experimental technique, and (3) industrial applications, the study covers these in the following way:

(1) The study provides a framework defining the current application domain of digital manufacturing tools and Industry 4.0 technologies that are used in each manufacturing life cycle phase. Many of the tools are not new, but recent forms of integration, improvements in use and joint use with advanced manufacturing technologies have changed the digital manufacturing field as a whole. This opens up several new opportunities. The study is important because having such a clear and well-defined application domain is essential to be able to create, plan and conduct a successful digital manufacturing implementation project.

(2) The study explores how DM operates in an Industry 4.0 context. Due to technological changes the way digital manufacturing is used has changed dramatically. As discussed in the paper, these new characteristics of digital manufacturing emphasize integration and connectivity, thereby creating a dynamic environment to both design and operations of a factory, product and manufacturing process.

(3) The study results do have several industrial applications. Given the modular feature of leading digital manufacturing solutions, companies looking to implement digital manufacturing typically have difficulties in understanding which tools best meet their needs. The study framework helps to better identify the set of tools that will deliver the appropriate value package. In addition, the study provides empirical examples of joint use of advanced manufacturing technologies that can leverage the added value of digital manufacturing use. The framework is already being used by two multinational companies for implementation of digital manufacturing in their industrial plants.

We hope readers find this both insightful and useful for better understanding the evolving application domain of digital manufacturing and its relation to the technologies of Industry 4.0.

Sincerely,

Elias Ribeiro da Silva.

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

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Abstract: Digitalization of manufacturing is on the industry application research agenda, as technologies of the internet of things are becoming available and adopted in large scale by many industries. This study analyzes the application domain of Digital Manufacturing while considering the new industrial paradigm. Based on the content analysis, joint applications of digital manufacturing 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 to a better understanding of the future challenges that academia and companies face by positioning digital manufacturing conceptually and delimiting its application domain.

Keywords: Digital manufacturing; Industry 4.0; Smart Manufacturing; advanced manufacturing technologies; 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, automation and robotics, additive manufacturing, and human-machine interaction, are unleashing innovations that change the nature and content of manufacturing itself. Industry and academia leaders agree that digital manufacturing technologies will transform all aspects in the manufacturing systems of value chains [1–3].

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 [4, 5]. Manufacturing becoming increasingly multidisciplinary was perhaps inevitable. From the combination of organizational sciences, such as Total Quality Management - TQM, Just in Time – JIT, Concurrent Engineering and Lean Manufacturing; with engineering science of CIM emerged the concept of digital manufacturing that highlighted the need for more collaborative product and process design [5, 6].

Although not a recent issue, two aspects are noted in the digital manufacturing literature. The multiple definitions of digital manufacturing converge to the central idea of manufacturing improvement using technology integration [7–13]**.** However, there is a noticeable difference in this convergence and the application domain. 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 [14]. 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. This also identified the interaction with technologies of the fourth industrial revolution, commonly called Industry 4.0. The study is organized as follows: section two covers the characteristics of Industry 4.0 paradigm, as well as its models and technologies; section three presents how Industry 4.0 technologies are used jointly with digital manufacturing systems and at which stage of the manufacturing life cycle each is used; section four discusses and presents answers to the research questions; and finally, section six presents the conclusions, contributions, and implications for theory and practice.

2. Industry 4.0 paradigm

Industrial production systems are being transformed due to a higher level of digitalization, which leads to an intelligent, connected and decentralized production, standing for a new level of organization, called ‘The fourth industrial revolution’ or ‘Industry 4.0’ [15, 16]. The core idea of Industry 4.0 is to use the emerging technologies in a way that business and engineering processes are deeply integrated making production operate in a flexible, efficient, and sustainable way [17].

Sousa Jabbour et al. [18] point out that the principles and technologies of Industry 4.0 influence how products are manufactured, as well as customers' perception of the value of products. These principles are the horizontal and vertical integration of production systems driven by real-time data interchange and flexible manufacturing to enable customized production [19, 20]. To achieve this level of integration, Industry 4.0 concept is associated with the technical perspective of a Cyber-Physical System (CPS) integrated into manufacturing operations and with Internet of Things (IoT) technologies into the industrial processes, which can be represented by smart factories, smart products, and extended value networks – vertical, horizontal and end-to-end integration. People, machines, and resources are vertically integrated, while companies are integrated horizontally across the value chain [15, 21, 22].

Industry 4.0 intends the optimization of value chains by implementing an autonomously controlled and dynamic production, through a full automation and digitalization processes [23–25]. In this way, manufacturing systems are updated to an intelligent level. It enables all physical processes and information flows to be available when and where they are needed across holistic manufacturing supply chains, multiple industries, small and medium-sized enterprises, and large companies [26, 27].

According to Wang et al. [27] to establish the global value chain networks, the Industry 4.0 describes a production oriented CPS that integrates production facilities, warehousing and logistics systems and even social requirements. In addition, Germany Trade & Invest [28] mention that the industrial value chain, product life cycles and business information technology combination must integrate the processes from the product design to production, supply chain management, aftermarket service and training.

Although the term Industry 4.0 is widespread, terms including Industrial Internet [29], Integrated Industry [30], Factory of the Future [31, 32], Smart Industry and Smart Manufacturing [33–35] are also used to address similar requirements and are subsumed by the concept of 'Industry 4.0'.

3. Digital Manufacturing in Industry 4.0

Being Digital Manufacturing under the umbrella of Industry 4.0 technologies and playing the role of to integrate technologies and information throughout the product life cycle, 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. A variety of concepts and solution-components were drawn and studied to fulfill the vision of Industry 4.0, and these technologies have significant influence on current manufacturing [36, 37]. The technologies include Cyber-Physical Systems (CPS) as intelligent entities in production or manufacturing, IoT as communication platform for CPSs, Cloud solutions for decentralized services, and Big Data solutions for high-performance processing of big data in manufacturing [15, 37, 38]. As observed by Rüßmann et al. [39], many 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, competences, capabilities, skills, and resource based views [32, 39–45].

However, the framework developed by the Boston Consulting Group, as presented in Rüßmann et al. [39], 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 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 digital manufacturing at different stages of the manufacturing life cycle, and impact it in terms of design, implementation, use or management.

To answer research questions, a 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. We explore next how the Industry 4.0 technologies influence design, implementation and use of various digital manufacturing tools. References are used from different fields to provide a comprehensive view, but with a weighting toward 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 Digital Manufacturing;

(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 order of technologies presented does not represent the relative weight of contribution in digital manufacturing, since the technologies may influence digital manufacturing in different ways.

3.1. DM and Simulation

According to Ribeiro da Silva et al. [14], digital simulation constitutes a core function in Digital Manufacturing, since it supports experimentation and validation of different scenarios and configurations for existing and new manufacturing resources and systems, contributing for an improved design and performance assessment. Simulation involves modeling of processes or systems, so that the model mimics responses of the actual system to events that take place over time [46]. In a fully integrated Digital Manufacturing 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. Such use of digital manufacturing is already presented in many companies around the globe [47–49].

The main difference lies in how simulation is being used today, and at which manufacturing life cycle phase. Digital Mock-ups were the foundation for CAD systems and discrete event simulations for predicting performance. However, the emergence of cloud technologies and real-time data acquisition allows simulations that have migrated from a static and deterministic environment to a more dynamic and stochastic environment. Manufacturing in fact is facing the revival of ‘hardware in the loop’ control systems design techniques.

Real-time scenario analysis involving variables such as machines and equipment conditions, logistical and labor issues, enables simulations to improve targeting and resource selection for a given set of products and processes. The simulation results comprehend scenarios that maximize the use of finite resources available, a significant reduction of waste and line stops, quality improvement and cost reduction. This makes significant difference by allowing analysis of complex scenarios and creating dynamic decision-making mechanisms that is 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).

Sinha [50] described a case in an automobile company that aimed to synchronize conveyor system and Electrified Monorail System. They used real-time simulation carried out on Delmia for detecting process planning errors. The 3D simulation enabled to verify the motion of equipment's that helped in detecting crashing and trafficking on the assembly line system. Results provide better efficiency of machines and maintained the balance of the assembly line, avoid the trafficking and delay in manufacturing.

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. Increasingly, autonomous robots are programmed with artificial intelligence to recognize and learn from their surroundings and make decisions independently. 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. According to Fitzgerald [51], 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. Palmarini et al. [52] highlight applications of collaborative robots or '*cobots*': robots projected to physically interact with humans in a shared workspace, suited for flexible manufacturing environments since they are designed to be safe to deploy around people without guardian, operating autonomously or with only limited guidance. Cobots not only perform preprogrammed tasks, but also make decisions as necessary when the situation arises.

The main role of autonomous robots in digital manufacturing is to support design and simulation of autonomous or hybrid workstations. Digital manufacturing 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 Digital manufacturing tools adhere to. Several use case simulations are possible and validated through the Virtual Commissioning environment [53].

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 Stephane [53] using digital manufacturing 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, in real-time simulations the collaborative tasks between humans and robots DM tools assisted to find the optimal position for the worker in terms of ergonomics and security.

Wadekar et al. [54] described a task-based risk assessment process conducted in the early stage of layout design and building of a collaborative cell for sealing application performed in aircraft industries using a industrial robot system integrated with safety control functions. According to authors, Digital Manufacturing simulation tools were much required to see the demonstration of the robot task as well as the operator task, use of reachability analysis, creating the robot workspace envelope and dimensioning and positioning of the collaborative system in order to identify the hazards which were possible to eliminate.

3.3. DM and Cloud

The emergence of cloud computing represents a fundamental change in the way Information Technology 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 [55–57]. According to Mell and Grance [58], 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. For instance, as pointed out by Wu et al. [59], 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 computer-aided design (CAD), computer-aided engineering (CAE) or finite element analysis (FEA), and computer-aided manufacturing (CAM) software over the Internet. Thus, manufacturing companies may cut operational and capital costs, and free IT departments to focus on strategic projects rather than keep datacenters running. This type of service outsourcing has emerged as a possible solution to some of the problems encountered for proper use of digital manufacturing.

The use of digital manufacturing technologies requires a robust data infrastructure regarding data storage, transfer, and processing. Data storage is required in large servers, since the files are usually large and in great quantity, while data transfer support network sharing of files in a fast, secure and structured way, mitigating loss of productivity. Finally, high processing power is required for both analysis and simulations that demand high capacity of hardware for execution. Providing the sufficient infrastructure is a key obstacle to the effective use of digital manufacturing, and cloud is an appropriate technology solution.

The main role of cloud technology in digital manufacturing 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 digital manufacturing 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 cloud supports collection and makes data available in real-time for simulation, commissioning and operations management.

An example of application is the Siemens *Intosite* [60] that presents a simple and intuitive access to up-to-date digital manufacturing and production information from the shop floor. The solution deploys the digital factory as a software as a service (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

For Minerva et al. [61], IoT is mainly concerned with unique identifications, connecting through internet, and given accessibility to "things". Manufacturing operations have been taking advantage of digital-physical coordination for decades. Evolving technologies are making digital manufacturing more valuable, and the Internet of Things (IoT) is a key element. According to Turbide [49], 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 digital manufacturing 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 results dissemination obtained to assist decision-making in an efficient and effective way.

The interaction of process and digital product with real-time resources data provides 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 for operational production risks mitigation.

IoT connected 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 that IoT are used within digital manufacturing tools: (i) to allow full process and material synchronization, since plant integration and real-time simulation increases operational excellence; (ii) for predictive maintenance, since providing data for equipment analysis helps prediction accuracy.

3.5. DM and Big Data & Analytics

Columbus [62] comments that the manufacturing industry generates more data than any other sector. The more complex a manufacturing operation is, the more valuable the insights gained 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. [63] 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 backward looking reporting on past events, data is being used to predict trends and anticipate needs [64]. 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 [65].

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

Big Data and Analytics are typically employed to better use digital manufacturing 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 digital manufacturing tools more accurately [65].

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 over internal networks and/or over the internet. 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. Advantages of digitalization are discussed as ways to improve productivity and competitiveness. But as the degree of digitalization and connectivity increases, systems also become increasingly more susceptible to security vulnerabilities [66–68].

Wu et al. [59] highlight that the main role of cybersecurity in digital manufacturing 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 un authorized 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. [59] 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 part 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 digital manufacturing 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, or even videos) rendered onto a real environment [69, 70].

We divided the application of AR in digital manufacturing tools in two main forms. First, AR is a means by which ideas are produced and modeled. The technology assists to produce what is seen in the digital model. The idea is built from the interaction of something real. It can be a prototype of the product or the factory floor, with options for virtual development. This is not limited to the development of products, but also to the development of processes and resources. Second, as scope AR supports the visualization of what has already been produced digitally. Applications for training, implementation and operationalization of processes developed through digital manufacturing technologies are examples of this. In addition, the technology enables feedback from the factory floor.

Several key features of digital manufacturing are related to decision making and validation of both product, processes and resources. AR technology supports this through 3D immersion that enables contextual visualization with parameters of real scenarios and allows detailed analysis. In addition, most of the technologies available today (eg HoloLens, MagicLeap, Oculus Rift, Morpheus) already provide user interaction. This makes the creation, analysis and validation processes more collaborative and integrated.

Thus, the main role of AR in digital manufacturing is to provide an overlay of virtual information onto the real world in real-time, allowing fast, integrated and accurate decision-making. As presented by Nee at al. [70], 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).

An example of AR application joint with digital manufacturing is presented by Ong et al. [71] 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) or *3DPrinting* is defined by a range of technologies that translate virtual model data into physical models or prototypes. Using AM processes can be conducted directly from 3D design, without the necessity for intermediate process or tooling such as injection molds. The physical object is obtained through a process of depositing successive layers of material of a finite thickness. According to Davia-Aracil and Hinojo-Pérez [72], AM also facilitates the manufacture of short production series or customized products, even spare parts. The more complex a product and its manufacturing operations are, the more valuable digital manufacturing is. Despite a significant development in AM technology, Paritala et al. [12] point out that it still requires more insight into the microscopic and macroscopic aspects of manufacturing processes and systems.

The main role of AM in digital manufacturing 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 great precision, resulting in pieces visually identical to the planned product. Adjustments can then be proposed that only would be noticed later on the actual manufacturing assembly line. This reduces time and costs of developing a new model.

Conversely, DM assists in the preparation and validation of AM process to 3D printers. It helps save time and energy by archiving best practices for reuse, automatically optimizes part positions, create supports for developing different strategies for the additive process and implement a variety of 3D printers and additive systems with multiple outputs [73].

For instance, Renishaw [74] describes the use of digital manufacturing tools to provide printable AM files, aligning virtual and real worlds of 3D design, test and analysis software and metal 3D printing. This aimed to remove the need for the export of native CAD source files in a universal .STL triangulated file format, since it introduced manufacturing errors and was prime cause of loss of quality control. Following an iterative, closed-loop sequence of hinge design adjustment, simulation, printing and precision inspection, the AM built rules to achieve optimal 3D design and printing. As a result, the digital manufacturing tools allowed for printed parts produced more accurately, bringing lead time and material cost savings.

3.9. Summary

To address research questions, this section discussed the various technologies of Industry 4.0 and how they influence how digital manufacturing is used, as well as identify new opportunities. In the next section results and their implications are discussed further.

4. Discussion

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

4.1. Application domain of Digital Manufacturing in Industry 4.0

The first research question sought to define the current application domain for Digital Manufacturing in Industry 4.0. For this, previous section explored Industry 4.0 technologies, their interactions with digital manufacturing tools and their applications in different stages of the manufacturing life cycle. The growing increment of technologies that are being made available for industrial use, the technological changes that have been taking place, in line with the new paradigms of production and consumption (such as *servitization*), means that we must address the issue of application domain within a time horizon.

Studies, such as by Noh [75], present five manufacturing life cycle phases and the presence of DM tools in only three of them. However, the application domain of digital manufacturing was clearly expanded due the new tools offering by DM solution providers and the rise of several new technologies that can be used jointly with digital manufacturing. Thus, in this study the manufacturing life cycle was divided into eight phases to better understand the function of digital manufacturing tools. These phases are: product engineering, process planning, line balancing, plant design, assembly analysis, assembly validation, ramp-up for operations, and production management.

Fig. 1 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 that are 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.

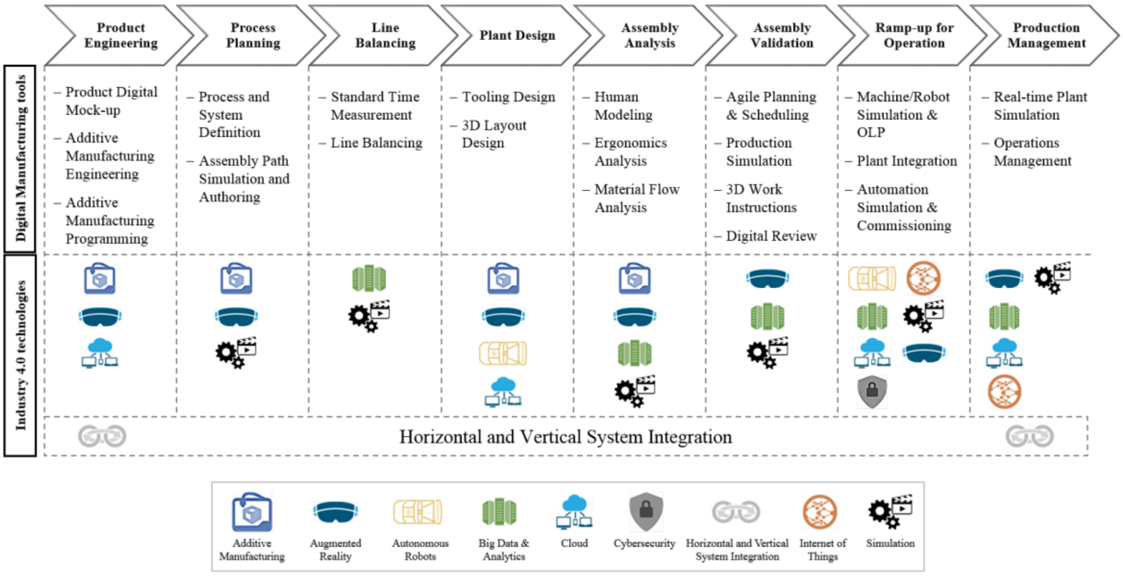

Fig. 1 Application domain of digital manufacturing in Industry 4.0

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 to choose 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 solution providers, such as Siemens with Tecnomatix [6] and Dassault Systèmes with Delmia [76].

As such, the framework provides information on which Industry 4.0 technologies are addressed based on the choice of value package selected. It is noticeable that some technologies can be used in several phases, while others only are used in specific phases. For instance, AR can be used to assist phases from product engineering to production management. In contrast, autonomous robots are mostly used only in the layout planning and the ramp-up for operation phases. Therefore, how solution providers classify tools in three main focuses are partially adjusted to the technologies. The three focuses are: Design-centered DM, which has functions for support design and engineering tasks; Production-centered DM that supports manufacturing preparation tasks; and Control-centered DM which deals with monitor and control by direct interface with production systems and machines on the shop floor. Technologies that focus more on control functions such as IoT and Cybersecurity are only seen in the later life cycle phases. Others which have a design and production function, such as AM, are consequently seen in earlier life cycle phases.

Having answered the first research question through the framework presented in Fig. 1, that defined the application domain for digital manufacturing in the context of Industry 4.0, next we analyze how digital manufacturing is operated in this new industrial context.

4.2. Operating Digital Manufacturing in Industry 4.0

The second research question explores how DM operates in this new context. Section 4 addressed the influence of Industry 4.0 technologies. There is a new range of tools to help plan, integrate and simulate the manufacturing environment. Two key technology characteristics that stand out in are integration and connectivity. Regarding integration, it is worth commenting on three important DM types: vertical integration of processes, horizontal integration of the value chain, and integration of data, tools and systems (interoperability). The vertical integration of processes consists of integrating the processes of different organizational units and making data available and optimized in an integrated network. Horizontal integration stretches beyond internal operations from suppliers to customers and all key value chain partners. It includes technologies from track and trace devices to real-time integrated planning with execution [44].

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 allow information management throughout the product life cycle, a main DM function, 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-organizational integration, many organization 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.

However, having all the information integrated digitally brings serious risks, as discussed in the cybersecurity section. For instance, industrial cybersecurity cases of ransomware are increasingly common (such as NotPetya, WannaCry, GoldenEye, etc) and risks are not limited to data loss or capture, or financial risks. There are also, as cited by Sorel [77], risks in terms of downtime, reputational, brand and subsequent top-line revenue. Hence, organization becoming digital and integrated must commit to constant cybersecurity vigilance.

5. Conclusions, contributions and implications for theory and practice

This study offered a new framework defining the current application domain composed by tools and Industry 4.0 technologies that are 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 DM field as a whole, opening up several new opportunities. This is important because presenting a clear and well-defined application is essential to create, plan and conduct successful DM implementations. Also, it was presented how DM has operated in Industry 4.0 context. Due to technological changes the way DM is used has changed dramatically over the last few years. As discussed, the new characteristics of digital manufacturing refer to integration and connectivity, creating a dynamic environment to design, redesign and analyze the factory, the product and the manufacturing process.

The study while contributing to a better understanding of digital manufacturing in this new industrial revolution presented some limitations since does not covered all technologies that have emerged in recent years (e.g. artificial intelligence, blockchain, virtual reality) being restricted to the nine technologies presented in the selected framework.

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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Figure

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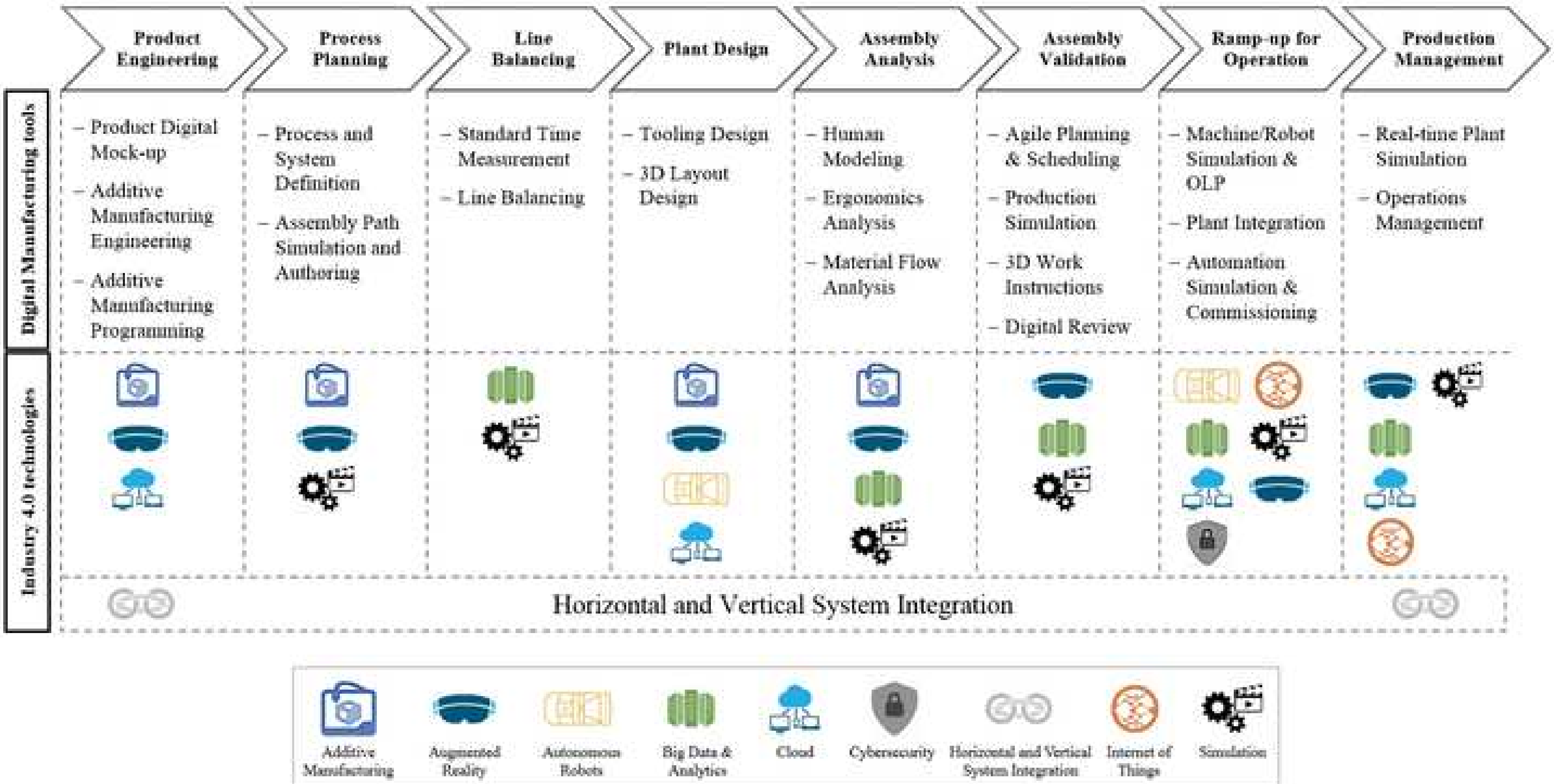

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In pursuit of Digital Manufacturing

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Abstract

Companies are adopting several new technologies that form the pillars of Industry 4.0 production framework, of which Digital Manufacturing (DM) stands out by combining conventional manufacturing technologies with digital techniques. These are used to assist in the design and analysis of the product and manufacturing processes. The adoption of digital manufacturing is partly about technological change, but it also entails significant organizational issues, which often are overlooked by managers. The purpose of this study is to identify the key factors that enable or prevent DM implementation, considering the production paradigm of Industry 4.0. Based on a literature review that identified a preliminary list of key factors, the appropriateness of these factors is empirically tested and refined in a two-fold approach: an in-depth pilot case in a multinational automotive company that is adopting DM technologies, and a survey of 113 users, managers, implementers and researchers working on digital manufacturing and Industry 4.0. The study identified 24 key factors to be considered when firms implement DM. These are categorized into technical, organizational, project based and external factors. The findings also indicate how each factor should be considered, and that they cannot be generalized due to cultural differences inherent to each individual company. As such, this research contributes to the current research debate by identifying the critical factors to be considered when conceiving and applying models for planning and executing DM implementation.

Keywords: Digital manufacturing; Industry 4.0; critical factors; implementation process; survey.

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1. Introduction

The digital revolution is in many ways driving industry transformations. Alongside technological advances, the subtler but powerful drivers of social and behavioral change have also prompted mass consumption industries to evolve [1]. The digital transformation is being developed under Industry 4.0 production paradigm, which is essentially based on the adoption of Cyber-Physical Systems, the Internet of Things and the Internet of Services [2].

Digital manufacturing (DM) is increasingly gaining importance in this technology-based scenario as one of the areas of knowledge within the Industry 4.0 agenda. DM is a set of technologies used for information management that assists decision-making throughout the product 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. Previous studies have shown that publications on DM have increased, with several researches conducted on associated technologies, some of them on content models, few case studies and a lack of in-depth studies of the implementation process [3–7]. There are studies on Critical Factors for digital manufacturing, but they did not consider the new digitalized manufacturing context. Thus, many relevant variables, both for implementation and use, have not been included in the analyses. This led to the following research question: "What are the critical factors for the implementation and use of digital manufacturing in an Industry 4.0 context?" [8,9].

The study addresses the gap in knowledge by aligning researchers' knowledge and professional expertise on critical factors to develop a digital manufacturing adoption framework. To answer the research question, four specific objectives are pursued: (1) to identify critical factors for digital manufacturing implementation in the context of Industry 4.0; (2) to conduct an exploratory case study to map the roles that these factors play in DM implementation; (3) to survey experienced professionals in digital manufacturing implementation and use, to review the mapped factors and assessing their importance for DM implementation, and; (4) to analyze the relationships involving the list of identified factors that influence DM implementation. In combination, these objectives provide the necessary information for identifying and refining a list of the critical factors for DM implementation.

2. Research design

The research strategy sought to combine academic and industrial knowledge. Thus, two steps of refinement are performed on the preliminary list of factors. Figure 1 presents an overview of the research design.

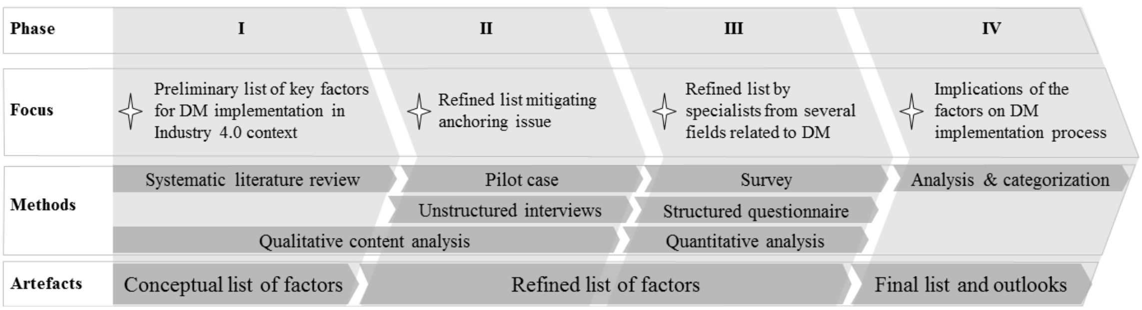

Fig. 1 Research design

2.1. Exploratory Case structure

The exploratory case is in fact the first technical refinement of factors. The procedure is performed using unstructured interviews with employees working on digital manufacturing implementation in a multinational company that is adopting an Industry 4.0 production framework. The choice of using unstructured interviews in this phase is justified for obtaining the lowest level of anchoring, thereby enabling the test whether or not the responses of staff dealing with the implementation process in practice correspond to what is identified in the studied DM BoK. An improved but still preliminary list of factors is obtained [10,11].

2.2. Survey structure and data analysis

Having reduced the anchoring problem in the first phase, a survey questionnaire is developed for the second technical factor refinement. A questionnaire test is carried out to ensure the data collection is applicable in a real-world scenario. The test is conducted according three key groups: (i) users from industry that use various DM tools; (ii) consultants who assist on DM implementation processes, and (iii) researches exploring DM use. The survey is then applied to professionals working with digital manufacturing. The survey is more comprehensive than the test, since it incorporates a greater variety of respondents, such as users, managers, implementers and researchers on digital manufacturing and Industry 4.0 from several countries, enterprises, and research institutes. This has the benefit of supporting the capture of the broader organizational changes related to technological change.

The questionnaire contained 31 questions and is divided into five blocks: (1) sample characterization; (2) questions related to technical aspects; (3) questions related to organizational aspects; (4) question related to project management; (5) questions related to external aspects. Likert scales are to measure opinions, perceptions, and behaviors. Only questionnaires that contained answers to all questions are considered for analysis.

The collected data is initially tested for index stability using Cronbach Alpha. This coefficient does not simply measure test homogeneity, as could be used to test reliability. A longer test increases its reliability regardless of whether the test is homogenous or not. It is recommended to have an alpha score between 0.70 and 0.90 [11–13].

The reliability test for the data collected resulted in a Cronbach's alpha of 0.850. The same test is applied to the four constructs: technical, organizational, project management and extern. The alpha values for the constructs are 0.862, 0.785, 0.692 and 0.750, respectively. These results show that the data as adequate to assess the DM implementation factors. A total of 113 complete questionnaires are received. Table 1 presents the sample composition of respondents based on their main professional activities.

Table 1 - Main professional activity of respondents

Professional Activities	**Frequency**	**Percent**
Industry	23	20,3%
Consulting	11	9,8%
University or R&D centre	78	69,0%
Other	1	0,9%
Total	**113**	**100%**

The cut-off points are based on the global average of concordance. Factors that present average above the superior cut-off point or below the inferior cut-off point are analyzed. Factors within the cut-off points limits are kept as critical factors.

3. Results and analysis

The results cover multiple refinements of a list of factors, and have they starting point at the literature review.

3.1. Literature review

In a previous study, Shinohara et al. [14] conducted a SLR based on papers and technical reports to identify factors that are critical to DM application. The review is also concerned to connect the factors to Industry 4.0, since projects in this new paradigm are not only related to technical issues, but also require organizational changes. It is presented a list of factors based on the ‘Risk Breakdown Structure’ proposed by PMI, as shown in Table 2.

The first category refers to ‘Technical Factors’, that is closely related to infrastructure, such as software, hardware, and system configurations, but is poor for Industry 4.0. However, the literature on Industry 4.0 point out new features for improved use of D, such as traceability, cybersecurity, connectivity and the ability to obtain and treat big data. The second category refers to ‘Organizational Factors’ that cover the economic viability, development of capabilities, and characteristics of organizational culture, such as an innovation-driven environment, rapid responses to new developments, and top management support and commitment for long-term returns.

Table 2 Critical Success Factors for Digital Manufacturing in Industry 4.0

Categories	CSF for DM implementation in the context of Industry 4.0	
Technical	TF1	Data management interoperability related to tools and systems integration
	TF2	Infrastructure, operating system speed and ease software configuration (computers, networks)
	TF3	Real-time data
	TF4	Connectivity
	TF5	Ability to transform Big Data into knowledge and decision-making
	TF6	System architecture that support data from IoT
	TF7	Advanced robotics
	TF8	Cybersecurity
	TF9	Traceability
	TF10	Logistic automation
	TF11	Technical support for DM tools
	TF12	Availability of collaborative tools
Organizational	OF1	User knowledge
	OF2	Training programs (project team, support team, decision-makers and users)
	OF3	Collaborative organizations with self-training teams
	OF4	Centralized management of products, processes and resources
	OF5	Dynamic design of business processes and engineering
	OF6	Innovation-driven culture
	OF7	Employee adherence, commitment and participation
Project Management	PMF1	Implementation strategy (communication, planning, scope, objectives, roles, responsibilities, change management and support)
	PMF2	Economic Viability
	PMF3	Financial Resources
	PMF4	Composition of the project team
	PMF5	Internal and external communication
	PMF6	Research and development model change
	PMF7	Support and continuous commitment of top management
Extern	EF1	Partners with knowledge and experience
	EF2	Greater customer focus

The third category refers to ‘Project Management Factors’ (PMF). This category could be considered an extension of the previous category, since they are organizational factors directly related to the implementation management. It includes factors related to the development of communication skills, enabling a collaborative environment and dissemination of the implementation strategy, which is closely related to change management.

The fourth and last category refers to ‘External Factors’ (EF) that cover the integration with external suppliers, partnerships with companies to exchange knowledge, greater focus on customer needs, and a government macroeconomic analysis to understand the feasibility of project implementation.

3.2. Exploratory case

Twelve interviews are carried out with employees from different departments that encompass: product and process engineering, layout development, equipment development and IT. The departments are consulted for capturing a complete and systemic view of the company situation in relation to DM. Open questions are used, allowing each interviewee to present their vision and experience on the difficulties found in DM implementation. Of the 31 factors identified in the literature review, 13 are also cited as critical during the exploratory case. Most of these are related to the organizational dimension. In addition, three new factors are added, as shown in Table 3.

Table 3 – Added factors after pilot test

Categories	CSF for DM implementation in the context of Industry 4.0	
Organizational	OF8	Rapid responses to market technological developments
	OF9	Workload management to enable innovation activities
Extern	EF3	Integration with external suppliers

Two of the added factors are organizational and the other a external one. Content analysis shows that the root cause of many problems during DM implementation are due to a lack of appropriate environment, as well as a very slow response to market developments. This is correlated both with the lack of innovative environment, and with political aspects that are external to the company. An example of the latter is protectionist strategies, which make it difficult for companies to acquire certain technologies. The difficulty to work jointly with suppliers in an integrated platform give rise to the last external factor. After the exploratory case, 31 factors constituted the critical factors list.

3.3. Survey results

More than 70% of the respondents answered that they have high knowledge (competent or expert) in the subject. Only 6% declared themselves novices or advanced beginners. Most of them work on Production Planning and Simulation (63.9%), 3D Layout Design (40.2%), Product Digital Mock-up (37.1%), Machining Simulation (31,9%) and Material Flow Analysis (27.9%), Human Modeling and Analysis (26,8%). More than 90% of respondents work with more than two DM tools. This information is important since it shows respondents work in the three phases of digital manufacturing: Design-centered, Production-centered, and Control-centered.

Of the 12 technical factors identified, 9 of them had above-average concordance and, according to respondents, are essential for successful implementation and use of DM tools. Factors related to interoperability (94%), real-time data (92%), connectivity (91%) and traceability (89%) have the highest concordance regarding their neediness for DM adoption. TF2 (71%), TF7 (48%) and TF10 (68%) are out of the cutoff point (See Fig. 2).

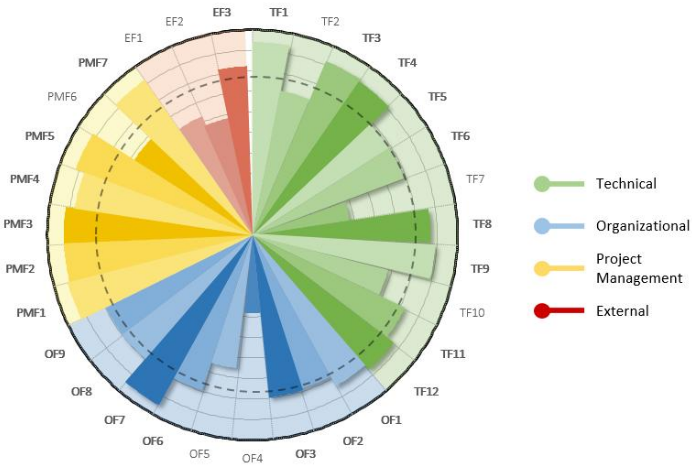

Fig. 2 Survey results

However, despite TF2 – that refers to the requirement of a better infrastructure and operations system speed than is commonly found on the shop floor for DM tools to work properly – obtained 72% of concordance, it is worth noting that 24% of the academics and researchers group selected the option 'neither', meanwhile respondents from the industrial and consulting environment, who deal directly with the technological difficulty related to day-to-day processing time, present a rate of concordance over 88% and only 3% disagreed. From this more contextualized data analysis it is possible to infer that this factor did not reach a high level of concordance because it directly is related to unfamiliarity of this technological requirement by academics. Because of this, TF2 is added to the list.

Organizational factors are not only bounded by DM implementation, but they are also required for its use and optimization. Survey results show that of the nine organizational factors identified, seven of them presented above-average concordance. Factors related to user knowledge (84%) and employees commitment (95%) appeared with the highest rates. Factors OF5 and OF6 are removed, since they are mischaracterized as critical factors.

Factors categorized as project management could be no longer critical after the technology implementation, since they are not required to operate and optimize the use of the technology. Of the six PM factors identified, five of them had above-average concordance as being critical for a successful implementation. PMF6 is the only project management factor with a relatively low rate of concordance, being removed from the list.

Finally, regarding external factors, only one out of three factors had concordance above the cut-off point. Results show that the only external factor that is critical is the integration with external suppliers (EF3). EF1 which refers to a requirement of partners with knowledge and experience in DM, had 30% of neutral responses. This rate is even higher among the group of consultants, which over 50% respondents providing a neutral response. These numbers are worth mentioning because there they show that rather than a disagreement, there is an apparent neutrality. This let infer that such partnerships are not essential for the success of the implementation and use of DM, despite in some cases create value added. The factor EF2 shows similar results, referring to the need for greater customer focus, which presented 36% neutral answers. This factor also had low rates of discordance.

In summary, of the 31 factors initially identified, 24 of them are considered by survey respondents as critical to the success of the implementation and use of DM in Industry 4.0.

4. Discussion

Having explored critical factors for DM implementation and use in the analysis, a holistic view of the results is presented below. Several aggregated conclusions are drawn:

a. **Several technologies provide competitive advantages but are not critical for a successful implementation and use of Digital Manufacturing**: Technologies associated to Industry 4.0 do have the potential to substantially change the manufacturing processes. They could increase the value added of projects when used in conjunction with digital manufacturing. However, some of them are not intrinsically critical for an implementation nor for its later use. They also need a specific context for their value to be captured. But, note, the fact that certain technologies are not essential for DM implementation does not invalidate the argument that they could bring competitive advantages. In addition, their adoption has allowed some factors not to be more critical, such as the centralization of product, process and resource information, where decentralization of this management along the supply chain is already a positive factor.

b. **The more substantial the knowledge of DM, the greater the value obtained by the joint use with Industry 4.0 technologies**: The results indicate that the higher the users knowledge, the greater the concordance that such technologies improve the results obtained from the joint use with DM. This relationship is not surprising but corroborates the alignment perspective among the new characteristics of digital manufacturing and Industry 4.0. Although DM has existed for more than 30 years, its current characteristics are recent and closely related to the pillars of Industry 4.0: connectivity, integration, decentralization and virtualization.

c. **Trade-offs are found among the factors: even among factors validated as critical for the implementation and use**. Since the integration with external suppliers (EF4) depends on the systems interoperability (TF1), if the systems are the same, the exchange of information and the use of collaborative tools (TF12) is allowed otherwise there could be limitations. In practice, DM systems that meet the demand of required features by large enterprises and enable internal integration, in terms of cost (OF4) are prohibitive for SMEs. This shows a trade-off related to internal and external integration, based on the economic perspective of the supply chain. Another example is related to rapid responses to market technological developments (OF8) and cybersecurity (TF8), since the guarantee of cybersecurity for new technologies implementation is not something rapid or easy to reach mainly in complex environments.

d. **Practitioners have more clearer opinions than researchers regarding the adoption of digital manufacturing**. The results suggest that there is a considerable difference between the answers of researchers (universities and research centers) to those from practitioners (industrial environment and consulting). In 76% of the cases, the practitioners have lower rates of 'neither' answers when compared to the researchers. This difference is even greater when considering technical and project management factors, reaching 89%. In relation to PM factors, it is noticeable that the practitioners present a greater rate of concordance about the criticality of the implementation team composition and on knowledge management. Regarding technical aspects that involve knowledge about the day-to-day of the application, such as infrastructure, connectivity and technical support, significant differences are also perceived. However, for the organizational and external factors those differences are within the limit of statistical tolerance to not be considered significant.

5. Conclusions

In this paper, critical factors for DM implementation process are discussed. The results presented here could assist managers to more carefully and accurately design DM implementation projects. The exploratory case conducted in an automotive multinational company and the survey conducted with 113 professionals allow to compile a list of 24 factors that are considered critical and should be carefully analyzed before DM adoption.

Having summarized the findings in the discussion above, three main conclusions can be drawn from the results: a) since organizational culture has great influence in the implementation of this type of projects, detailed implementation recipes tend not to work. This study explored factors that should be extensively discussed among stakeholders involved in the implementation process of digital manufacturing. However, the way each factor should be treated must be contingent to its operations environment; b) what perhaps makes this type of project different from other implementation projects is the culture change that needs to occurs behind it. It is not just about technology change, but also about radical changes throughout the product life cycle, directly interfering with how and when each activity could and should be done; c) change does not occur periodically, it could be continuous or event driven. Organizational capabilities need to be managed, as the employees' capabilities.

The paper, while contributing to a better understanding of DM in this new industrial revolution, has a number of limitations. The first is that the number of respondents per professional activity are not equal, presenting a higher number of researchers than manager and implementation consultants. The second limitation concerns the lack of weights for criteria. This is done intentionally to better illustrate relevant factors, since explicitly weights could lead to a discard of lower scored factors and depending on the company specific situation the weightings may vary. The third limitation is that what stage of the implementation process each factor should be considered is not presented.

In this sense, next efforts will focus on the development of an implementation framework. The goal is to develop a process to assist managers to an effective DM adoption focusing to develop a theoretical model to better understand what the critical factors are in each phase, and to conduct case studies to refine the implementation framework.

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Paper 5

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Towards Digital Manufacturing in Industry 4.0: A comprehensive framework

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1. Introduction

The digital revolution is in many ways driving industry transformations. The increasing unpredictability in the business world exposes all participants to unprecedented uncertainty, and selecting technologies is of strategic importance to face this turbulent environment. The selection of technologies is one of the most challenging decision-making areas the management of a company encounters (Ejsmont, 2017; World Economic Forum, 2016). As manufacturers face significant economic, competitive, regulatory, and technological challenges, they look to technology to survive. (Humphlett, 2014). This has led to the pursuit of technologies found in the Industry 4.0 production framework. In it Digital Manufacturing (DM) stands out by combining conventional manufacturing technologies with digital techniques. In short, Digital manufacturing is a set of tools used to design, redesign and analyze the factory, product and manufacturing process in an integrated way (Ribeiro da Silva *et al.,* 2019). However, its adoption is partly about technological change, but it also entails significant organizational issues which often are overlooked by the management.

Although DM already is in use, there have recently been several technical changes and their application domain in production. This is mainly driven by the new industrial context and the rise of advanced manufacturing technologies. These changes led the European Commission (EFFRA, 2016) to position DM as one of the five key priorities for the FoF 2020 - Factories of the Future - the strategic proposal presented under the Horizon 2020. This seeks to encourage some implementation initiatives in synergy with the ongoing waves of Industry 4.0. According to them, DM enables the provision of services that support manufacturing in a broad sense. These services are associated with collecting, storing, processing and delivering data. These data are either describing the manufactured products or are related to the manufacturing processes and assets that make manufacturing happen (material, machine, enterprises, value networks and factory workers).

But there is limited information on the process of implementing and then managing DM in this new context, which prevents successful DM adoption. Therefore, based on data from six multinational companies, this study provides a tailored framework to support the process of DM implementation and use. It seeks to answer the research question of what type of characteristics a framework has tailored for DM implementation and appliction. Based on the critical success factors that have been identified in previous researches (eg. Ribeiro da Silva *et al.,* 2019; Shinohara *et al.,* 2017), the developed framework deepens the understanding of activities managers must undertake to successfully employ DM considering the technological paradigm of Industry 4.0.

The paper is organized as follows. Section two presents the theoretical background, including critical success factors for DM in an Industry 4.0 context. Section three presents the research design, including the case study and interview protocol. Results and framework proposition are presented in section four, followed by a discussion for operationalizing the framework in section five. Concluding remarks, conceptual contribution and practical implications are then presented in the final section.

2. Theoretical Background

The debate of how digital technologies reshape manufacturing industries has been raging for decades, covering computer-integrated manufacturing, digital economy, and recently Industry 4.0 which incorporates emerging technical advancement (Reischauer, 2018; Zhong *et al.,* 2017). Industry 4.0 describes the fourth industrial revolution, with an intelligent, connected and decentralized production. Focus is on digital and virtual technologies, and it is driven by real-time data interchange and flexible manufacturing, enabling customized production (Drath and Horch, 2014; Li *et al*., 2017). de Sousa Jabbour *et al*. (2018) note that the principles and technologies of Industry 4.0 influence both how products are manufactured and customer perception of their value. Manufacturing systems are updated to an intelligent level that takes advantage of advanced information and manufacturing technologies to achieve flexible, smart, and reconfigurable manufacturing processes to address an increasingly dynamic and global market (Hartmann et al., 2015; Wang et al., 2016; Zhong et al., 2017).

2.1. Digital Manufacturing in Industry 4.0

Digital manufacturing is a set of tools used for information management that assists decision-making throughout the manufacturing life cycle. DM is concerned with product and process representation in a digital way, but also in integrating technologies and business areas across the product life cycle (EFFRA, 2016; MESA, 2016; Turbide, 2016). However, due to technological changes the way DM is used has changed dramatically over the last few years. While not all individual technologies are new, recent forms of integration, improvements in use, and joint use, have changed the technology role, as seen by the expansion of the DM application domain. Based on new technologies and integrated ways of applying them, DM provides comprehensive advantages in all manufacturing life cycle phases: product engineering, process planning, line balancing, plant design, assembly analysis, assembly validation, ramp-up for operations, and production management (Ribeiro da Silva *et al.,* 2018) But realizing the expected benefits of DM requires a clear project scope definition, identified difficulties and benefits in each phase, and specialized training in the early implementation stages (Shinohara *et al*., 2017). This highlights the necessity of good understanding of the conditions that influence the adoption process, as well as the use of a guiding framework.

2.2. Critical Success Factors for DM in Industry 4.0

Research on technology implementation suggests that successful implementation is multi-faceted. It may gainfully be stratified in that there are generic factors that affect any type of change process, and particular factors that affect organizational improvement efforts in a more narrow sense, and factors unique to the implementation (Keathley-Herring, 2017). For instance, the study by Ribeiro da Silva *et al.* (2019) on Critical Success Factors (CSF) is appropriate for DM adoption in an Industry 4.0 context. This identified 24 key factors for successful DM implementation. These were categorized by the four categories on the Risk Breakdown Structure proposed by PMI (2017) (See Table 1). The categories are technical, organizational, project based and external factors.

[INSERT TABLE 1 HERE]

The technical factors category are related to infrastructure, such as software, hardware, and system configurations. It also includes new features for improved use, such as traceability, cybersecurity, connectivity and the ability to obtain and manage big data. The organizational factors category covers economic viability, development of capabilities, and characteristics of organizational culture. This is exemplified by an innovation-driven environment, rapid responses to new developments, and top management support and commitment for long-term returns. The project management factors category covers the development of communication skills, enabling a collaborative environment, and dissemination of the implementation strategy. Finally, the external factors category covers integration with external suppliers.

While several technologies provide competitive advantages, not all are critical for a successful DM implementation and use. Technologies associated with Industry 4.0 do have the potential to substantially change manufacturing processes and increase their value add. But they need a specific context for their value to be captured, preferably linked with the pillars of Industry 4.0: connectivity, integration, decentralization and virtualization (Dalenogare *et al.,* 2018; Ghobakhloo, 2018; Lu, 2017).

2.3. PPDIOO Digital Manufacturing meta-framework

In exploring a suitable DM framework, this section presents a meta-framework to reflect the various phases of a DM life cycle in the Industry 4.0 context that is analogous to the PPDIOO methodology proposed by Froom *et al.* (2010) that is applied to reflect the various phases of a typical network's life cycle. PPDIOO is an acronym for Prepare, Plan, Design, Implement, Operate, and Optimize. The use of a lifecycle approach provides several key benefits, such as lowering project total cost, improving business agility and planning for infrastructure changes and technology requirements. Each phase is defined below according to its specific DM purpose:

- **Prepare**: Define viability of using digital manufacturing tools. This preparation includes alignment of top management with demanding resources, organizational changes and long-term goals;
- **Plan**: Project planning in its managerial, financial and strategic phases;
- **Design**: Implementation project design in its techniques and forms of applicability within the pre-determined scope in the previous phase;
- **Implement**: Implementation of the DM system and training for appropriate use;
- **Operate**: Projects running with digital manufacturing tools in a connected and integrated way internally and externally.
- **Optimize**: Use of resources to optimize the ongoing operation process, aiming at the implementation of new ways of delivering value through DM.

Defining the specific purposes supports the research protocol development that is presented in the following section. The phase purposes are also the basis for the proposed deliverables the results generate. Since unique organizational culture typically has significant influence in DM implementation, detailed implementation recipes tend not to work. Thus, each phase seeks to present a logical structure by which factors should be extensively discussed among the stakeholders.

3. Research Design

The study is based on several case studies operating in different sectors, regions and stages of implementation, as suggested by Voss *et al*. (2002) and Saunders *et al*. (2015) to contribute both conceptually and for practice. To operationalize the cases, several semi-structured interviews were conducted to explore the factors critical for DM adoption in an Industry 4.0 context in each phase. The interviews also helped to understand how each company uses planning, analysis, implementation and management of DM, and how this is integrated with the environment. A sample of six companies were selected (See Table 2), representing companies of different sizes, complexity, sectors and DM tools used. The companies sample encompassed three countries, from Europe and South America, which presents a research virtue since cultural aspects influence DM adoption in every lifecycle phase. Having several companies with diverse conditions helps raise awareness and in turn control for the cultural element.

[INSERT TABLE 2 HERE]

The interviews identify the company maturity related to Industry 4.0, and the DM role. In some cases, several people had to be interviewed for all question to be answered, since individuals lacked the necessary information to answer all questions. In other instances, one interviewee possessed enough comprehensive information to suffice. Interviews with representatives from companies three and six were conducted in person, while the other interviews were conducted online using the software Skype for Business. In addition to the interviewer taking notes throughout the interviews, all the interviews were recorded for later consultation as needed. Since not all interviews were conducted in English, some citations in the Section 4 have been translated (where applicable, this is marked in the text). During the actual interviews, to capture how each organization use DM tools and how it is aligned to Industry 4.0, a brief initial characterization was conducted. Table 3 presents the DM system used for each organization, length of use, integration with suppliers and with legacy systems, capture and use of real time data, as well as if the technology adoption is reactive or proactive solving problems and exploring new opportunities. Taken together it provides an understanding of how each organization employed and evolved in using DM.

[INSERT TABLE 3 HERE]

4. Results

This section presents each of the six framework phases. Based on the case results the section links critical success factors to respective phase. Some quotes extracted from the interviews are presented as examples of how companies deal with each critical factor.

4.1. Phase 1: Prepare

The initial analysis of DM adoption is largely related to the economic feasibility of using the toolkit. This preparation includes alignment of top management with demanding resources, organizational changes and long-term goals. The interviews revealed that economic viability analysis is used made prior to decisions on technology adoption. This helps negate the risks of pursuing complex and costly technology adoptions.

> *"The feasibility depends on context, demand. The greater the demand for projects and the more complex the projects are, the more viable the implementation becomes" (Manufacturing Engineer - Company 5)*

Several studies have shown that among the organizational factors that characterize such economic viability are issues such as development of high complexity projects, extended value chain, frequent changes in product range and time-to-market as a critical factor (Ehrhardt and Behner, 2016; Ribeiro da Silva, *et al*., 2018; Siepen *et al*., 2018). Even organizations that already use DM solutions may have difficulties in migrating to updated versions because of lacking clarity of any additional benefits.

> *"We have been using digital manufacturing solutions for 15 years. We have been looking at migration for the upgraded version [of the DM solution] for a year and a half but we do not have clear conclusions if it is cost-effective" (Head of Technical Discipline / Company 1)*

Managers also need to analyze the actual direct and indirect gains from the new functionalities in product, process and resource utilization. For instance, a recent new functionality within DM platforms is the management of digital twins (Dassault Systemes, 2018; Siemens, 2018). However, most of the sampled organizations do not have the capabilities to run this functionality, so it would bring little or no financial return having it.

Successful implementation also depends on a top management commitment to the project. This is also seen in several studies of ERP implementation projects that have similar characteristics in terms of complexity and organizational changes (Baykasoğlu and Gölcük, 2017; Chang *et al*., 2015; Chofreh *et al*., 2018; Sørheller *et al*., 2018). As noted by one manufacturing engineer:

> *"It is important [the commitment of top management] because, does not matter how good the tool is, it will not work if the leader does not know how to conduct implementation and how to work within the system. […] They do not need to know how to use the tool, but they need to know the basics, the work methodology" (Manufacturing Engineer - Company 5)*

The strategic activities and decisions performed by senior managers influence the business processes, and as mentioned by Chofreh (2018), enable control over the information and activities of the project.

4.2. Phase 2: Plan

The planning phase deals with project planning in its managerial, financial and strategic phases. It is here important to develop an implementation strategy that includes factors related to technology selection, process mapping, availability of financial resources, selection of people involved in the project, development of internal and external communication channels, as well as to define the roadmap for implementation. One project leader highlighted this:

> *"It certainly pays off [the implementation of the DM System] as long as it is well implemented, if it has an implementation strategy, if well used. Simply buying the system and believing that digital manufacturing will work is illusory" (Innovation Project Leader / Company 6)*

The definition of the appropriate set of DM tools is dependent on several contextual variables and sector of operation. The portfolio of leading suppliers for DM solutions such as Siemens (2018) and Dassault Systèmes (2018) characterize the set of available tools, and research studies such as Noh *et al*. (2006), Choi *et al*. (2015) and Ribeiro da Silva *et al*. (2018) help define the set of tools appropriate for the specific organization.

As a modular system that allows selection of tools and required licenses, it supports a high degree of customization. A consultant noted that:

> *"[...] But for most companies there is no need for all licenses. So the modular structure of the solution is great because you can only pay for the tools that you need. [...]Not necessarily the set of tools that our company needs will be the same as the competing company" (External consultant / Company 3)*

A successful strategy builds on implementing basic tools in the first phase, such as tools for process analysis, layout development, trajectory analysis or ergonomics, before adopting more complex tools involving production management. This allows for a gradual learning process, and short term less drastic changes in the work methods. The roadmap for the adoption of new tools must be linked to the development of new personal and organizational capabilities.

Potential conflicts of interest between vendors and buyers typically push for the acquisition of a broader set of tools than is needed for the initial project phase. This locks in capital and generates lower ROI, as well as discourages organizational learning. One DM engineering phrased it as:

> *"The tools are not being fully used. Usually only a fraction of the purchased potential is used which is the minimum necessary" (DM Engineer / Company 2)*

This type of solutions influences technical aspects, work tasks, and organizational inter-departmental relationships. Using a unique and reliable data base to work in an integrated and connected way supports detailed planning. It does require more time spent in the initial planning of the project but provides a lower rework rate in the ramp-up for production. A DM engineer also highlighted the benefits gained:

> *"The concept of work using digital manufacturing is very different. [...] The production phases overlap, and people work in a more integrated way. You get a total development of the project still in the engineering phase, not only half project. Even those who work on product design give their opinion and may improve the process. [...] Project time decreased, rework decreased, and cost consequently decreased because we only need to do the job once. [...] being able to validate everything virtually has improved our response time when facing problems" (DM Engineer / Company 2)*

To realize these benefits, it is important to create internal and external communication channels. The internal channels support end-to-end inter-departmental integration across the manufacturing lifecycle, while external channels help integrate the supplier network and external partners.

4.3. Phase 3: Design

The design phase deals with the implementation project design in its techniques and forms of applicability within the pre-determined scope set in the previous phase. This includes infrastructure sizing, DM system choice considering interoperability strategies and a long-term vision, definition of systems to be integrated, strategy for ensuring connectivity and data capture, as well as the development of channels for supplier integration.

DM systems work with relatively large amounts of data, in addition to the simulation capabilities requiring a high processing capacity. An appropriate infrastructure capacity is critical, ranging from hardware to network capacity for data transmission. Computer process capabilities must be aligned to the DM tools. For instance, planning to use tools for 3D layout design or assembly trajectory require less processing capacity than those seeking to perform plant simulations with real-time parameterization. Devices to be integrated into the system must also be selected, such as virtual reality devices, design table for factory planning, and mobile devices. In terms of network capacity, it is necessary the sizing (or adaptation of the existing network) considers the amount of data transmitted.

A common problem is that DM systems consume a high degree of the existing network capacity, which generates bottlenecks in the analysis process. Time is lost as users waits for a part or process element to be loaded into the system. An appropriate sizing of hardware and network assists in better utilization of the workforce capacity. Managing risks, consideration should be given to the operationalization of sizing, acquisition and implementation since several companies may not have developed capabilities to deal with this kind of project. One DM researcher also raised organizational barriers:

> *"The biggest difficulty [for acquiring infrastructure] that I see is IT. It is too slow, too much bureaucracy" (Researcher of DM / Company 4)*

However, the completeness of individual tools is not sufficient to determine the appropriate system for a specific organization. The degree of interoperability between DM and legacy systems must also guide choices to better exploit the existing data and capabilities. But identifying the specifics is not always feasible, as noted by a DM researcher:

> *"The information is very disconnected. Some people have updated information, some do not. So, I think that [company name] centralizing information can be the main advantage*

for it. What I perceive is that [company name] would have the greatest benefit would be having the right information at the right time. It's not plausible to think about anything else before to have that." (Researcher of DM / Company 4)

A long-term vision for systems integration and complete interoperability should guide the choice of the DM system. For systems with different languages and protocols it is necessary to analyze the systems throughout the manufacturing life cycle and identify which bring the greatest benefits on decision-making, and the complexity and cost of such integrations. Such selection requires an inclusive view to find the most appropriate system for an organizational end-to-end integration.

"When we had to choose the [DM] system, we had to choose the one that allowed us to integrate some other systems, such as MES. It is no use choosing the system that has the best tools for one situation or another, it needs to be the best system for the company as a whole, looking at what we already have and what we want to acquire soon" (Innovation Project Leader / Company 6)

Also, capturing real-time manufacturing data to improve the quality of simulations and faster response to change was stated by the interviewees as a requisite for DM in Industry 4.0. IoT devices play a key role in capturing this data in real time, as noted by a DM engineer:

"An example of IoT we already use is sensor-based collaborative robots and other sensors at the plant that collect, process and transmit data directly to the cloud, and the [other country] team analyze it in real-time to see work routine, if something is operating in abnormality, and when their predictive model finds something a message is sent to us so we can act at the exact point before the device breaks down. This is already a commercial product that we use" (DM Engineer / Company 2)

All interviewees remarked on the on benefits of using IoT, but only one of the case organizations use data from IoT in their simulations. This lack of use was justified as due to a lack of specific knowledge of the technology, poor systems integration and financial resources.

"We are not yet using IoT solutions for data collection, but we understand the benefits that data could bring to the production simulations. Critical errors could be avoided" (Coordinator of IT systems for production / Company 1)

An intrinsic dependency on connectivity allows for data collection and transmission in real time and with end-to-end integration. It also enables real-time communication between people, systems, and machines. It is exemplified by a DM engineer as:

A robot in the factory is automatically informed when there is a new order. It automatically picks up the necessary components at the warehouse for this order and puts them in the process. We have this kind of integration here. (DM Engineer / Company 2)

However, despite the existing internal integration, the case organizations do not have peer-to-peer integration with external suppliers. Instead, the integration is conducted indirectly. Suppliers are required to deliver projects as a raw document that are imported into the system as a native file. For example, an equipment project with kinematics developed by an external supplier is delivered in a native file compatible with the customer's DM system. It cannot be converted to STEP or STP formats since it then would lose much of information. The way it works is described by one DM user as:

> *"All company sites are integrated within the same database in the digital manufacturing system, and everyone [authorized] can access the data of these factories. Regarding suppliers, we require they send to us compatible files with the digital manufacturing system, and then we import it to the database. This is just not done peer-to-peer or in real-time because of security, but there is integration with them." (DM User / Company 3)*

Most interviewees explicitly mentioned security-related barriers hindering integration with suppliers using the DM system.

4.4. Phase 4: Implement

The four phase is related to the DM implementation and staff training for its use. The change in work methods that implementing DM involves require new and refined skills among the operators and managers, and commitment to maintaining these must be ensured. The effective use of DM tools is not a trivial issue. It requires a high degree of specialized knowledge. Thus, training programs are indispensable. The interviews also revealed that due attention to training not always is given, but when conducted external trainings are typically performed with the providers of the DM system and then replicated internally:

> *"Of course, the implementation pays off. The question is how the 'implementation' is done. Today the company has several modules of the Delmia that could be adding value but are being completely underutilized. People do not have appropriate training, they do not take advantage of the tool. They end up using very little of what they have" (Researcher of DM / Company 5)*

> *"There are several trainings with the DM system suppliers itself, I even have participated in several of these training programs at their headquarters. But this happens in the first moment. Once there are already trained people within the organization, then we only spread the knowledge internally with collaborative teams and dependence on supplier training become only for training in new tools" (DM User/ Company 3)*

For the staff commitment, it needs to be developed in three areas: (i) virtualization of the entire manufacturing life cycle; (ii) work methodology seeking organizational integration; and (iii) development of new skills and capabilities. Poor DM understanding may even reduce employee commitment, as noted by an engineer:

> *"The last projects we did at [company x] they did not even request the digital files, this shows that they will not continue the virtualization of the factory. On the other hand [company y] requests daily the update of the digital files, because they want to have the factory literally virtualized, what they internally call Factory 4.0. Some companies have not yet realized what the concept of Industry 4.0 is" (DM Engineer / Company 2)*

This new work methodology requires some paradigm shifts. In traditional organizations, teams often work on projects in a linear way and in organizational silos. For an effective use of DM, departments need to work more closely and spend more time in the early stages of the project, seeking a detailed planning, aiming less rework in the final stages. So there is a need for alignment between managers and users. It is paramount that managers align their expectations with the organization's long-term vision. Managers need to ensure sufficient learning time to the operators for them to learn to effectively work with the DM system. Realignment in the parameterization of the project phases must take place for the new model of work using DM tools to take place effectively.

> *"In this new model of work engineering time has certainly increased, it demands much time to build a project with rich detail, but it is cheaper to pay someone who is sitting in front of a computer, working on schedule, without overtime payments, than paying the labor of an entire team on the factory floor, working on tight schedule, with possibility of loss of production if the start does not occur within the agreed time" (DM Engineer / Company 2)*

However, as also argued by Wu *et al*. (2018), DM systems are becoming more accessible as manufacturing machines are increasingly retrofitted with sensors as well as connected via wireless networks or wired Ethernet. While advancement in sensing, artificial intelligence, and wireless technologies constitute a paradigm shift in manufacturing, cyber-attacks pose significant threats. There are risks of external intrusions, and risks related to the loss, theft, alteration, damage or exposure of data. As argued by two interviewees, in addition to technological barriers, there is a strong need to train operators to be aware of and deal with such risks:

> *"There are several commercial tools dealing with cybersecurity, but nothing would prevent someone with a pen drive steal the plant or product digital model" (Coordinator of IT systems for production / Company 1)*

> *"There is nothing specific about cyber security beyond the basic issues of access, firewall, etc. Since I have data access, nothing would prevent me to copy information on a external drive or to upload it to the internet and selling it to another company, for example" (DM User/ Company 3)*

The prevalence of such worries is mirrored in several recent studies on risk management and cybersecurity within Industry 4.0, dealing with issues ranging from network security to social engineering (Babiceanu and Seker, 2017; Bordel *et al*., 2017; Bracho *et al*., 2018; Flatt *et al*., 2016; Hatfield, 2018; Preuveneers *et al*., 2017; Tuptuk and Hailes, 2018).

4.5. Phase 5: Operate

This phase is related to projects running with DM tools in a connected and integrated way internally and externally. Once implemented, projects are developed, tested, and simulated with assistance from various DM tools. Operators work with a single, up-to-date data source. Thus, capabilities related to the use of collaborative tools (mainly for interdepartmental use), updating of data, traceability processes, technical support and collaborative teams are developed. Through self-learning teams the way to use the can be spread internally in an organic way with no dependence on third-party companies, as suggested by one interviewed engineer:

> *"For those who do not yet have knowledge using some tool, we provide a two-weeks basic training with an internal professional who mastered that tool. [...]The idea is to learn by practicing. They start with a simple project after the two weeks of training and they can clear up doubts with someone responsible for his training until they reach the point where they can develop a project by themselves, but it usually takes years" (Manufacturing Engineer / Company 5)*

Workload management and employee commitment is of course also needed. Many companies have failed to implement these self-learning teams for lack of strategic alignment or commitment. This is exemplified by a DM user who commented on colleague that:

> *"It may work, but it depends a lot on how it is operationalized. Here theoretically there is this person, but she does not do just that. She is not just focused on DM within the team. She is requested for many other functions. She uses only use her free time to spread her knowledge, if and when there is free time. I think it would work if the person was working only with this, or at least had available time to teach someone else how to do certain activity" (DM User / Company 4)*

Collaborative tools are useful for mitigating work in organizational silos. They foster a sense of commonality and shared operability, as noted by one interviewee:

> *"The criteria for using certain tools are different for product engineering and process engineering, for example. In the case of VR the requirements are very different, and it is difficult to find a solution that gives the visual quality that the design needs and the agility that the process engineering needs. [...] So you need to carefully evaluate which solution will allow the two departments to work together.*

The emergence of cloud technologies and real-time data acquisition allows simulations that have migrated from a static and deterministic environment to one being dynamic and stochastic. Manufacturing faces the revival of 'hardware in the loop' control systems design techniques. For instance, the use of real time data allows dynamic simulations to predict in real-time how changes of a current process (process planning) influence the material flow on the shop floor (assembly analysis). The collection and use of data in real time allows more precise and agile simulations and decision making, as stated by one DM engineer:

> *"They [managers] are already demanding a level of virtual manufacturing as detailed as the factory itself, already using the digital twin concept. All signs and all operations need to be in accordance with the factory" (DM Engineer / Company 2)*

The presence of technical support to deal with hardware, software, and network issues, from product engineering to shop floor operations, is fundamental to guarantee reliability in the collection, transmission and data use as well as performance analyzing it. Traceability assists in risk control and creates a reliable source of procedural records regarding the inclusion, modification and exclusion of data.

4.6. Phase 6: Optimize

This phase covers the use of resources to optimize ongoing operation processes to implement ways of delivering value through DM use. This is influenced by the response to new market developments and the use of big data and analytics. Market developments occurs either reactively with market solutions sought to solve existing problems in the organization or proactively with new technologies or analysis used to find opportunities. Technologies associated with Industry 4.0 may substantially change existing manufacturing processes. Even older technologies may in a new and integrated form create new capabilities and opportunities, in particular if used in conjuncture with DM. One interviewed DM user noted how this follows the alignment perspective among the new characteristics of DM and Industry 4.0.

> *"Some POC [proof of concept] are being made for the integration of DM with other Industry 4.0 technologies. [...]Many companies are coming to show us new technologies, make demos, etc. We even bought the virtual reality glasses recently, but we have not yet decided where it will be used, if at the process or product level" (DM User/ Company 4)*

However, strategic alignment with the long-term vision is important. Technology is only the means to which identified problems are solved and opportunities explored. Creating a roadmap that aligns a long-term perspective with how each technology adds value is necessary. One interviewed researcher stated that:

> *"It is necessary to focus a lot on this coordination. What I see are people seeking innovations but failing putting it in practice. It needs someone who coordinates closely, who says where each person needs to focus on a common end goal" (Researcher of DM / Company 4)*

For this, Big Data and analytics may be used to exploit such opportunities. They are typically employed in the planning stages, covering line balancing through to real-time production management. For instance, airplane manufacturer Boeing is integrating its entire value chain into a single platform, where digital continuity improves data and analytics capabilities, and consequently make DM tools use more accurate (Dassault Systèmes, 2017).

4.7. Framework Proposition

The Framework proposed in Figure 2 is composed of four categories, six phases, and twenty-four critical success factors. Each factor is related to one of the categories of technical, organizational, project management, and external aspects.

[INSERT FIGURE 1 HERE]

Investigating the cases revealed that aspects related to the first phases of DM adoption process are directly related to the project management category, so a feasibility analysis as well as an implementation plan should be carefully developed. This is similar to other technology adoption projects, with a key difference is in the need to change working methods. The implementation phase tends to be more extensive than the preparation and planning phases, while the operation and optimization phases are continuous. Note that the linear representation of the stages shown in Figure 2 does not represent an accurate timeline. The time lengths vary during the phases, and even change from one organization to another.

5. Discussion

This study has explored the process of digital manufacturing technology adoption in Industry 4.0. Seeking to fill the gaps in the literature and to explore the systematization of the critical success factors for its adoption, several interviews were conducted for a contextual analysis. As presented in the interviews analysis, the results show the many aspects that interfere in the success of adoption and contrast different perspectives, approaching studies in different contexts, segments and strategies used. The results provide two main insights. First, some lessons can be learned from previous projects that assist to apply the DM framework considering the main aspects and phases that organizations need to manage when adopting DM. Second, the research results generated deliverables for moving between the DM adoption phases. Both are addressed in the next sub-sections.

5.1. Framework capabilities

Previous projects of technological implementations such as ERP and other legacy systems, as well as process focused implementation such as lean and agile, support the DM adoption due to many shared critical factors and required capabilities. Sedera and Gable (2010) identified the importance of knowledge management to achieve enterprise system success, being the lack of sufficient support from knowledge management approaches throughout the project lifecycle one of the main reasons for implementation failures. An effectively managing a wide range of knowledge, which resides in multiple stakeholders has been identified as a crucial factor for enterprise system project success (Jayawickrama *et al.,* 2016; Lech, 2014). Thus, previous experience an organization adopting complex systems or technologies, such as an ERP system, is helpful for development of conditions such as accurate project planning and employee commitment to new work method. Studies show that several CSF are the same for adopting both systems. Both demands complex and detailed knowledge for successful implementation, being important to discover innovative methods, techniques and approaches that can integrate such knowledge among individuals and across stakeholder groups (Berraies *et al.,* 2014; Ram *et al.,* 2013). Besides that, integration, interoperability and connectivity all play important roles in DM framework as support for organizational change. Operational and organizational capabilities related to these issues need to be developed and have weaker links to legacy systems. Pursuing a single robust and up-to-date data source, fast and reliable data access, and internal and external integration with suppliers all support digital manufacturing. It also enables inter-departmental collaboration and facilitates an accurate and fast decision process which reduces rework in the final project phases.

In contrast, some criteria are specific to DM projects. Issues related to the acquisition, processing and analysis of real-time data to run dynamic and stochastic simulations are not required by other systems. Thus, the importance of the development of capabilities related to real-time data, fully connectivity and IoT devices differs from other technological adoptions. By having technological convergence with other advanced manufacturing technologies, rapidly response to new market developments is also a unique feature of DM projects. The dynamic environment and rapid technological changes are not comparable to the gradual and slow moving that occur with legacy systems.

In this sense, it presents characteristics more similar to process focused implementations such as lean and agile, which other capabilities can be exploited. First, agility is capability that allows thriving and prospering in dynamic, turbulent environment. The capability that makes organization able to respond to changing and differentiated requirements of customers, deal with competitive environment, evolving technologies and decreasing product lifecycles. (Stachowiak and Oleśków-Szłapka, 2018). Factors such as supply chain integration, leadership commitment and employee involvement in complex projects, developed communication channels intra- and inter-departmental, changing working culture can be cited similar success factors (AlManei *et al.*, 2017; 2018). R&D capability has an important role in absorbing knowledge generated elsewhere, and also refers to the capability to undertake frontier technology activities Moreover, upskilling and technological capability development are also indispensable (Radosevic and Yoruk, 2016, 2018).

Several capabilities ranging from technological to managerial should be developed to conduct such projects in the context of Industry 4.0. They are related to production, technological and innovation capabilities. The accumulation of technology embodied in successive generations of increasingly advanced physical capital, together with the accumulation of the associated human capital required to operate the production system efficiently represents the production capability. Lastly, the ability to create new technology, design new features of products and processes represents the innovation capability (Bell and Figueiredo, 2012; Radosevic and Yoruk, 2016; Szalavetz, 2018). To succeed in the DM operationalization and optimization, as well as for other advanced manufacturing technologies, it is pivotal organizations develop capabilities in these three dimensions seeking long-term learning skills.

5.2. Framework deliverables

Readiness is the extent to which an organization assesses that the project ran smoothly and problem free when it looks backwards at the end of project. In practical terms before the project starts, the overall readiness is also a measure of the extent to which the organization has put in place the employees' skills, resources and other factors which are necessary for the project to proceed smoothly and problem free. To develop the project plan for improving the readiness, the organization initially needs to know which activities should be performed to achieve readiness and what is the current state of readiness in the organization (Ahmadi *et al.,* 2015).

Hence, for each phase of the DM adoption process to be successful, some minimum requirements need to be met. Based on the proposed framework and developed cases, a set of deliverables for each phase of the process is proposed below. Due to be a sequential process, it is important that each stage meets these minimum requirements to minimize the risks of project failure. Table 4 shows the deliverables for each phase.

[INSERT TABLE 4 HERE]

As presented earlier, the transition time between each phase varies depending on the organization and project scope. But is the deliverables and their assessment must be completed before commencing the next phase. Such validation process increases process reliability and aligns expectations. Validation with top managers helps ensure commitment to the project as well as the resources for later phases of the project.

6. Conclusions, contribution and recommendations for future research

While digital manufacturing has existed for a few years, its current characteristics are closely related to Industry 4.0 in terms of connectivity, integration, decentralization and virtualization. This study offers a framework to assist organizations in the implementation and use of DM in the context of Industry 4.0. Grounded in theory and empirical cases, the study defined project phases and which factors are vital in each of these phases. Finally, it systematized the deliverables for appropriate project operationalization and management.

What makes this type of technology adoption project unique is the extensive culture change and work methodology that needs to occur. It is not just about changing the technology base, but about radical changes throughout the product life cycle, directly interfering with how and when each activity could and should be done. As such, it has more in common with process focused implementations such as lean and agile than with technology specific adoptions such as integrated IT systems (AlManei *et al.,* 2018; Rasnacis and Berzisa, 2017; Stachowiak and Oleśków-Szłapka, 2018). The study findings show that since organizational culture has significant influence on the implementation, detailed implementation recipes tend not to work. But for each adoption stage, the results indicate particular aspects and deliverables that need to consideration by the stakeholders involved in the implementation process.

6.1. Theoretical and empirical contributions

In terms of contribution, the study adds to the existing literature in investigating the new characteristics of DM in the context of Industry 4.0. It explored how these characteristics provide value to processes and products, identifying necessary deliverables at each adoption stage. It also found how digital manufacturing technology changes affect operational and organizational strategies and conditions. In terms of managerial implications, the results support managers that seek to adopt DM. This also helps managers understand implementation dilemmas and empirically explores several difficulties encountered in various phases of the framework and proposes ways to mitigate them. Finally, it shows managers that when seeking greater organizational maturity in relation to the principles of Industry 4.0, they will be able effectively absorb added value of the various advanced manufacturing technologies. The social impact of the current study can be reflected in a more effective coordination of manufacturing lifecycle while assisting the continuous improvement of products and services both in terms of quality, time-to-market e mass customization.

6.2. Limitations and recommendations for future research

In terms of study limitations, the choice of covered organizations and product offerings is limited to the sample. For capture of boundaries of DM implementation, this should be expanded to other type of organizations, such as small and medium-sized enterprises (SME). In addition, a continuation of the study should explicitly explore the implications of organizational maturity in the use of digital tools, since such management and staff experience and routines may impact on how DM is implemented. On a final note, the study is focused on organizational capabilities, which for a life-cycle perspective should next be expanded to an integrated value chain and ecosystem approach towards digital transformation.

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Appendix A. Interview template

Project title

Towards Digital Manufacturing in Industry 4.0: A comprehensive framework

Instructions

Brief overview of the research will be given before starting the interview by the researcher in order to ease answering process of the participant. However, when answering each interview question, try to address the key aspects of the research such as What, How, Why, With and Digital Manufacturing implementation success.

Interview questions

1. Are the organization adopting Industry 4.0 technologies (such as IoT, VR/AR, autonomous robots, etc.)?
2. How long have the company been using digital manufacturing system?
3. Which digital manufacturing system is used? (Delmia, Tecnomatix, etc.)
4. Is digital manufacturing really necessary for the company? What are the characteristics that make it needed?
5. Despite the costs of implementing and maintaining the systems, is it feasible to have digital manufacturing implemented?
6. Was the top management committed with digital manufacturing systems adoption?
7. Was there a team focused on the selection, implementation and integration of Industry 4.0 technologies?
8. Which other systems are integrated to digital manufacturing system? (ERP, MES, CRM, PLM, etc.)
9. Are the data used for the projects real time data? How are they collected (IoT)?
10. Is the factory floor connected to digital manufacturing system?
11. Are the company digitally integrated to their suppliers by DM systems?
    a. If yes: how is this integration designed and implemented?
    b. If no: why?

12. When the company started using digital manufacturing, did it changed how people used to work? Why?

13. Considering all information is digital, connected and integrated into one platform, how does the company handle the risks and ensures the safety of the operation?

14. How does work training in digital manufacturing tools for the employees?

15. How does the company respond to new market developments?

   a. Does the company seek opportunities to adopt new technologies OR adopt those technologies that solve problems related to the strategy?

Table 1 Critical Success Factor for Digital Manufacturing in Industry 4.0

Categories	CSF for DM implementation and use in the context of Industry 4.0	
Technical	TF1	Data management interoperability related to tools and systems integration
	TF2	Infrastructure, operating system speed and ease software configuration (computers, networks)
	TF3	Real-time data
	TF4	Connectivity
	TF5	Ability to transform Big Data into knowledge and decision-making
	TF6	System architecture that support data from IoT
	TF7	Cybersecurity
	TF8	Traceability
	TF9	Technical support for DM tools
	TF10	Availability of collaborative tools
Organizational	OF1	User knowledge
	OF2	Training programs (project team, support team, decision-makers and users)
	OF3	Collaborative organizations with self-training teams
	OF4	Innovation-driven culture
	OF5	Employee adherence, commitment and participation
	OF6	Rapid responses to market technological developments
	OF7	Workload management to enable innovation activities
Project Management	PMF1	Implementation strategy (communication, planning, scope, objectives, roles, responsibilities, change management and support)
	PMF2	Economic Viability
	PMF3	Financial Resources
	PMF4	Composition of the project team
	PMF5	Internal and external communication
	PMF6	Support and continuous commitment of top management
Extern	EF1	Integration with external suppliers

Table 2 Sample overview

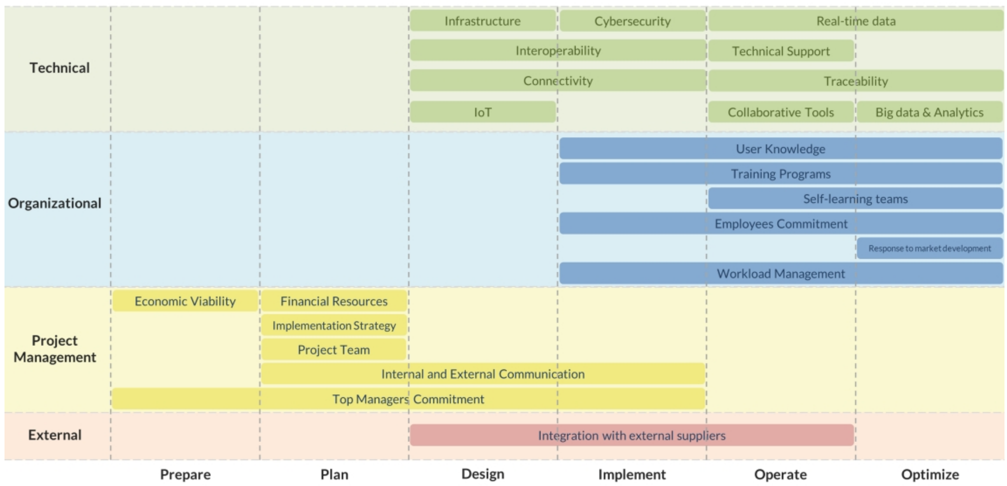
Organization	Sector	Job positions interviewed
Company 1	Aerospace & Defense	3 positions - Head of Technical Discipline - Manager of Manufacturing - Coordinator of IT systems for production
Company 2	Technology	1 position - DM Engineer
Company 3	Automotive	2 positions - DM User - External consultant of DM
Company 4	Automotive	2 positions - DM User - Researcher of DM
Company 5	Technology	1 position - Manufacturing Engineer for DM
Company 6	Automotive	1 position - Innovation Project Leader

Table 3 Companies characterization

Companies	DM System	Period since implementation	Integration with suppliers	Legacy systems integrated	Real time data	Technology adoption	
						Reactive	Proactive
Company 1	Delmia	10 years	○	○	○	●	○
Company 2	Tecnomatix	5 years	●	●	●	○	●
Company 3	Tecnomatix	4 years	●	◑	○	○	●
Company 4	Delmia	3 years	○	○	○	◑	◑
Company 5	Tecnomatix	7 years	◑	○	○	●	○
Company 6	Delmia	3 years	○	○	○	◑	◑

Table 4 Deliverables for the PPDIOO DM Framework

Phase	Purpose	Deliverables
Prepare	Define viability of using digital manufacturing tools. This preparation includes alignment of top management with demanding resources, organizational changes and long-term goals.	– Economic viability analysis verifying characteristics that justify DM use and implementation, such as project complexity, product range, supply chain extension and stability, speed of change of technology – Meetings with top managers to ensure project commitment for long-term benefits
Plan	Project planning in its managerial, financial and strategic phases	– Design the strategic plan for implementation, involving scope, objectives, responsibilities, communication channels and support – Release financial resources – Definition of responsible project team
Design	Implementation project design in its techniques and forms of applicability within the pre-determined scope in the previous phase	– Definition of infrastructure needed to implement the project – Design of systems integration – Design of integration with external suppliers – Design of integration with the shop floor *(if applicable)*
Implement	Implementation of the DM system and training for appropriate use	– Context presentation meetings for users addressing mid and long-term benefits for the company and users, and the difficulty of changing the way working. The commitment of users to the new way of working is a goal – Training programs for selected tools in scope – Implementation of accesses and security of internal data. Includes deployment of network firewalls, local firewalls, and application firewall for external security
Operate	Projects running with digital manufacturing tools in a connected and integrated way internally and externally)	– New projects delivered within DM system applying available tools
Optimize	Use of resources to optimize the ongoing operation process, aiming at the implementation of new ways of delivering value through DM	– Structuring periodic analysis of market developments and its DM applicability – Structured and periodic analysis of data collected to improve DM utilization and seeking new ways of delivering value through DM



PPDIOO DM Framework

253x190mm (300 x 300 DPI)