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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.
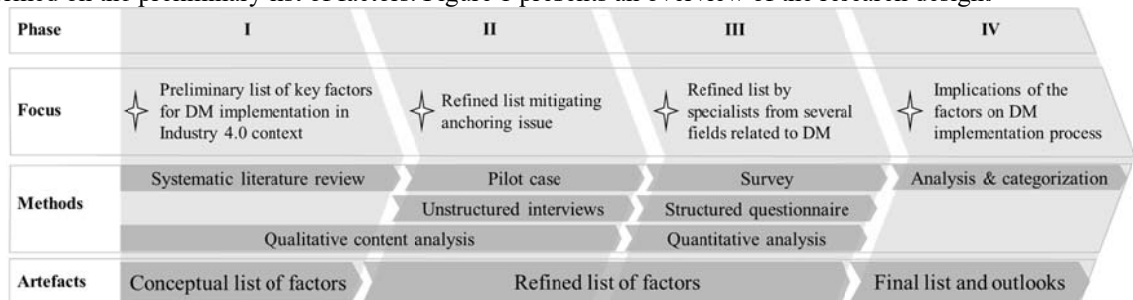

Phase	I	II	III	IV
Focus	Preliminary list of key factors for DM implementation in Industry 4.0 context	Refined list mitigating anchoring issue	Refined list by specialists from several fields related to DM	Implications of the factors on DM implementation process
Methods	Systematic literature review	Pilot case	Survey	Analysis & categorization
		Unstructured interviews	Structured questionnaire	
	Qualitative content analysis		Quantitative analysis	
Artefacts	Conceptual list of factors	Refined list of factors		Final list and outlooks

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.

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).
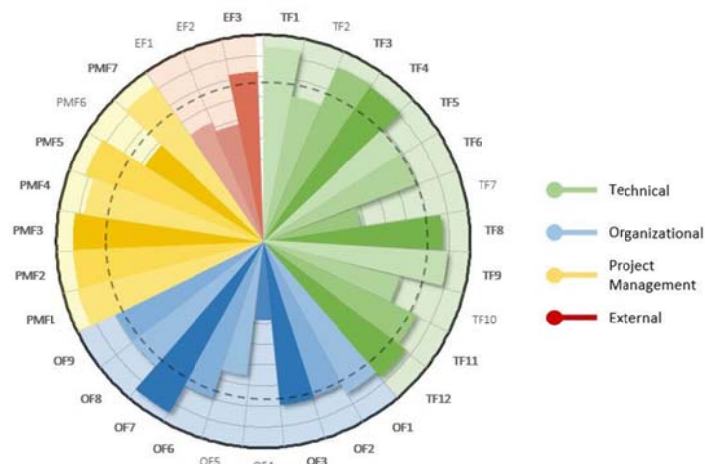

Fig. 2 Survey results

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.

Acknowledgements

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