Barriers and enablers to the implementation of Digital Twins in manufacturing companies: a literature review

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Abstract: The development of innovative simulation and integration technologies, led by Industry 4.0, brought increasing attention to the theme of "Digital Twins" (DT) in manufacturing. As a matter of fact, since 2016 the number of papers related to DT has been strongly growing in the industrial engineering body of literature. Articles, conference papers, and book chapters can be found, presenting models and applications of DT in different manufacturing realities. Also, reviews published from 2018 have analysed the current state-of-the-art and opened interesting future research directions in terms of DT methods, tools, and technological issues. These are key contributions to provide support to the decision-makers in integrating the benefits of different technologies and developing the idea of Smart Factory. However, achieving a successful DT-driven Smart Factory within industrial realities is a demanding task, and nowadays companies still struggle in understanding how to face the challenges related to create and maintain DT. These challenges are not only related to technological barriers, but also to managerial, cultural, and organisational barriers. Nevertheless, a complete overview of the barriers and the consequent enabling factors to DT implementation are still missing in the literature. Hence, the aim of this paper is to present a general overview of the literature on barriers and enablers to DT implementation and understand the current gaps that need to be filled in this research area. In doing so, the study conducts a systematic review of the literature on DT for manufacturing applications, presenting a descriptive and thematic analysis of the existing contributions. By analysing the DT literature, this article develops a taxonomy of the main barriers and enablers for the implementation of DT and presents a research agenda to define future research directions and guide new contributions to the DT knowledge.

Keywords: Digital Twin; Manufacturing; Industry 4.0; Barriers; Enablers; Literature Review

1.Introduction

The innovative technologies of Industry 4.0 (I4.0) paradigm can lead to major improvements in the overall operations performances, enhancing the efficiency of the processes as well as lowering waste of time and resources (Havard *et al.*, 2019).

In the last few years, the discussion and the attention around Digital Twins (DT) has strongly grown, driven by the huge steps forward in use and optimisation of I4.0 technologies. DT models represent a disruptive technology that could allow optimal integration of the I4.0 tools. NASA in 2012 defined DT as "*an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, and so forth, to mirror the life of its flying twin*".

Therefore, DT can be defined as an integrated simulation technology that can be exploited in order to create a high-reliable model of the behaviour of an environment and to generate insights and provide feedbacks, e.g. predictions of future issues in the physical part of the twin (Tao *et al.*, 2019). Thanks to data recovered directly from the field by sensors and the ability to communicate and elaborate data in real-time from the physical twin to the virtual one, DT represents a breakthrough in the simulation technologies (Negri, Fumagalli and Macchi, 2017).

With the development of new tools and technologies that enabled a more efficient way to transfer, store and elaborate data, DT models are now evolving into integrated models applied to the manufacturing world (Lu *et al.*, 2020), which correspond to the digitalised version of the industrial environment considered, i.e. a single machine, an entire factory or a logistic system.

However, unlocking the potential and the benefits of a DT is not an easy task. The challenges of DT implementation are not only related to technological barriers, but also to managerial, cultural, and organisational barriers. Indeed, the implementation process of this new technology requires a deep knowledge of the physical behaviour to be modelled as well as the development of strong infrastructure to support data transmission and elaboration (Moreno *et al.*, 2017).

Furthermore, as highlighted in several reports (McKinsey, 2018; ARUP, 2019; Deutsche Post DHL Group, 2019), the implementation of DT has to address the typical issues that characterise the introduction of new technologies in a company, such as lack of high skilled competences as well as a possible resistance to change. Achieving a successful DT-driven Smart Factory within industrial realities is a demanding task, and nowadays companies still struggle in understanding how to face the challenges related to create and maintain DT.

This problem recently increases the interest of literature on these issues, searching for solutions and enablers to help companies in overcoming the heavy barriers to achieve an implementation of a DT model that could be rewarding and value-maker. Articles, conference papers, and book chapters can be found, presenting models and applications of DT in different manufacturing realities. Also, reviews have been published, which analysed the current state-of-the-art and opened interesting future research directions in terms of DT methods, tools, and technological issues. These are key contributions to provide support to the decision-makers in integrating the benefits of different technologies and developing the idea of Smart Factory.

Nevertheless, a complete overview of the barriers and the consequent enabling factors to DT implementation are still missing from the literature. Hence, the aim of this paper is to present a general overview of the literature on barriers (i.e. obstacles to DT implementation) and enablers (i.e. possible countermeasures to the barriers) to DT implementation and understand the current gaps that need to be filled in this research area. To achieve this aim, this paper performs a systematic literature review, which seeks to provide answer to the following research questions:

- *What are the barriers to DT implementation?*
- *What are the enablers to DT implementation?*
- *What are the future research challenges for DT literature?*

The next session presents the description of the materials collected and the methodology applied in the review. Sections 3 presents the descriptive analysis of the barriers and enablers, describing all the categories and critically analysing all the papers contributing to them. Finally, the future research directions are discussed in section 4.

2.Materials and Methodology

The database used to gather the papers for the systematic literature review of this study is mainly referred to Scopus, as it provides a wide and spread literature on scientific and management matters. The literature search on Scopus aimed to achieve the largest number of relevant papers related to the DT. Therefore, the search process was performed including a general search field as "TITLE-ABS-KEY".

The keywords chosen for the analysis of the literature on DT were firstly determined in order to be as wide-spread as possible, but still aiming at Industry 4.0-related papers. Hence, the keywords used first were "Digital Twin" and "Industry 4.0". The second keyword has been considered in order to build a literature review which focuses on DT as a pillar of Industry 4.0. Furthermore, this keyword allows to strongly focus on Industry 4.0-related papers, and therefore to provide a heavily manufacturing-related contribution. In order to provide research that could include as much literature as possible, the keywords had been enlarged, adding "product avatar" and "digital shadow". These successively considered keywords were deductively determined in the process of analysis of the literature. Thus, the following string of search was used: (TITLE-ABS-KEY ("digital twin") OR TITLE-ABS-KEY ("product avatar") OR TITLE-ABS-KEY ("digital shadow")) AND TITLE-ABS-KEY ("Industry 4.0"). Using these keywords, a total number of 244 papers were found (last extraction was done on March 1st, 2020). The search output was then filtered to include only journals, which constitute a reliable source of information both for the novelty (Cronin, Ryan and Coughlan, 2008) and the quality of the citations (Lin *et al.*, 2017). Finally, only papers in English were included. This leads to a final number of 68 papers considered.

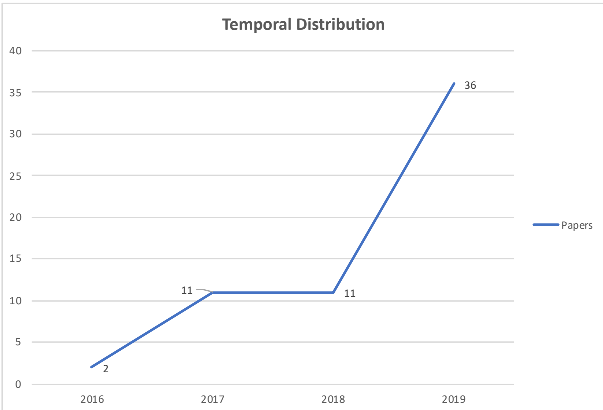

Figure 1 : Temporal distributions of papers over years

Figure 1 shows the temporal distribution of the papers over the years. It provides the evidence of a positive trend in the interest of the scientific community to the DT topic. As a matter of fact, 2 papers of the selected ones for this literature review were published in 2016, whilst in 2019 this number rises to 36. This strong rise in publications highlights the importance of the theme of DT and therefore the need of further studies on this technology. In the temporal distribution the number of papers published in 2020 is not reported, as the data related to this period are still incomplete. However, papers belonging to that period are included in the review.

The journal distribution underlines that there are four journals highly interested in papers related to DT theme, i.e., *IEEE Access, IFAC-PapersOnLine, Journal of Manufacturing Systems, Applied Sciences.*

3.Barriers and Enablers to DT implementation

From the analysis of the literature, a categorisation of the main barriers and enablers has been developed. Since no evident categories have been found in the literature, these have been constructed deductively.

3.1 Barriers to DT implementation

The identified barriers to the implementation of a Digital Twin model are twofold. Firstly, there are barriers related to a technological component, that could generally represent a high edge especially for Small-Medium Enterprises (SMEs) due to the economic effort needed to implement the DT enabling technologies. Secondly, there are knowledge-based barriers, as an extensive and specific knowledge component is needed in order to develop, run and control a DT.

Therefore, from the analysed literature two main categories of barriers to DT implementation have been defined, i.e. *technological barriers* and *knowledge barriers*.

Technological Barriers. In order to develop a DT, very complex and expensive technologies are needed. In the literature four main typologies of barrier are discussed. Firstly, a relevant issue for a DT development is the need for reliable and fast Internet enabled connections. As a matter of fact, the communication between the physical twin and the digital twin rely on Internet-enabled connections, where the major challenges are the development of a global connectivity, integration and interoperability of all systems in the digital twin, strong data security and data integrity, capability of collecting and computing reliable data in real-time and develop of centralised, simplified and standardised models (Redelinghuys, Basson and Kruger, 2019). Secondly, a DT needs a pervasive presence of sensors and actuators technologies, which represent an important prerequisite for digital twins (Negri, Fumagalli and Macchi, 2017; Cohen *et al.*, 2019; Redelinghuys, Basson and Kruger, 2019). Therefore, the challenge is to develop complex systems able to fill this need. Thirdly, there is a relevant need for the capability to collect, process and store a massive amount of data. As a matter of fact, DT needs for collecting and processing data in real-time, requiring a very high computation capability (Tseng *et al.*, 2019). Finally, as the amount of data is highly relevant, the theme of the control over data is particularly significant. Indeed, combining physical and digital behaviours can lead to a lack of control over data, since the integration between the different data sources is complex and may cause possible data corruption. Therefore, the challenge for this barrier is to control data and avoid data fragmentation (Havard *et al.*, 2019).

Knowledge Barriers. The development of a DT implies the need for extensive and highly specialised knowledge both for the physical twin and for the virtual twin. The first knowledge barrier identified from the literature regards the need for a deep knowledge of the physical behaviour of the simulated and emulated object. Physical behaviour is the set of physical laws that rule over the simulated objects. For the developpement of a digital twin is necessary to fully describe the behaviour of the physical objects to provide a realistic and reliable twin. This is a very technical and complex knowledge, which is not always available within industrial realities (Moreno *et al.*, 2017; Geris *et al.*, 2018; Tugengol'd *et al.*, 2019). On the other hand, the second knowledge barrier regards the need for high competencies to run and control DT. In DT there is a strong need for integration with the human component to provide a necessary interaction to control and run the model. However, DT systems are not known by most of the SMEs due to a lack of competences concerning Industry 4.0 matters. Hence, the challenge is to make the DT structure, as well as the challenges and benefits of their implementation, well known within SMEs (Uhlemann *et al.*, 2017; Havard *et al.*, 2019).

Table 1 synthesises the barriers to DT implementation identified in the literature.

Technological Barriers		
Barrier ID	*Barrier*	*References*
I	Need for strong internet enalbled connections	Redelinghuys, Basson and Kruger, 2019
II	Need for sensor-actuators technologies	Negri, Fumagalli and Macchi, 2017; Cohen *et al.*, 2019; Redelinghuys, Basson and Kruger, 2019
III	Need for high computation capability	Tseng *et al.*, 2019
IV	Need for control over data	Havard *et al.*, 2019
Knowledge Barriers		
	Barrier	*References*
V	Need for deep knowledge for digital twin development	Moreno *et al.*, 2017; Geris *et al.*, 2018; Tugengol'd *et al.*, 2019
VI	Need for high competences to run and control digital twins	Uhlemann *et al.*, 2017; Havard *et al.*, 2019

Table 1: Barriers Categories

3.2 Enablers to DT implementation

As far as the enablers for the implementation of DT concern, one main typology has been identified. As a matter of fact, the literature provides almost only enablers related to the technological and technical components.

However, the *technological enablers* category is rich in elements which could be highly helpful in order to break down the barriers to DT implementation. A total number of 11 technological enablers have been identified.

The first enabler considered is the development of a structured information model. With this tool, meant as the detailed representation of the physical object, the developers could set the baseline for the unique description and definition of the object or process to be modelled (Lu *et al.*, 2020).

The second enabler regards the development of a communication network which could allow a bidirectional communication between the physical and the virtual part of the DT. Moreover, this network should be performing enough to enable the transmission of the communication data between the real and the virtual environment in real-time (Negri, Fumagalli and Macchi, 2017; Lu *et al.*, 2020). The development of a fully automated flow of data between the physical and the virtual environment is another enabler which follows the development of a bidirectional communication network (Redelinghuys, Basson and Kruger, 2019).

Another enabler is the development of a processing method for the analysis of the massive amount of data collected in real-time, i.e. Big Data. Moreover, in a DT model the function of Big Data processing is twofold. Firstly, the method should be able to extract hidden meaning from the data gathered. Secondly, there should be an effective capability of processing data in real-time. However, in order to provide the maximum benefits, the processing method should be fed with high-quality data only (Lu *et al.*, 2020).

An interesting enabler is the development of a proper decision-making structure. In order to fulfil this purpose, the AI technologies could provide relevant help. However, a decision-making structure could help in building a DT able to provide optimum solutions and decisions, enhancing the level of independence of the DT model itself (Redelinghuys, Basson and Kruger, 2019).

In order to gather data from the physical environment, it is necessary to develop a proper method for collecting data. Data could be collected by a complex system of sensors and actuators. Hence, a relevant enabler for DT implementation is the development of Cyber-Physical Systems (CPS) and the use of the main Industry 4.0 technologies. CPS could be defined as complex and multi-dimensional systems whose main goal is to collect data from sensors and therefore to connect and integrate the physical and the virtual environment (Negri, Fumagalli and Macchi, 2017; Urbina Coronado *et al.*, 2018; Cohen *et al.*, 2019; Redelinghuys, Basson and Kruger, 2019; Wang and Wang, 2019).

The development of a proper information repository is a key enabler in order to efficiently store the massive amount of data gathered by sensors. Thus, data can be aggregated and organised in order to provide ready access and allow real-time data processing (Redelinghuys, Basson and Kruger, 2019). Furthermore, data should be structured using a semantic data model, which enables the continuity of data in the system (Negri, Fumagalli and Macchi, 2017).

Another relevant enabler to the implementation of a DT is the development of a simulation and emulation system. The former aims at providing data and information but mostly predictions of the future behaviour of the simulated system. On the other hand, the latter is needed to provide an exact and accurate representation of the emulated system (Redelinghuys, Basson and Kruger, 2019). As it concerns DTs, both simulation and emulation systems are particularly relevant and delicate issues as they represent the core of the DT. As a matter of fact, a key enabler for a successful implementation of DT is the development of a simulation and emulation framework, intended as a tool which can provide the needed interaction between all the different single emulation and simulation technologies. In this way, the DT could reach a high level of integration that is necessary in order to exploit all its potential benefits (Negri, Fumagalli and Macchi, 2017).

Finally, an interesting enabler is the development of a *Digital Shadow*. The Digital Shadow is a particular simulation and emulation model structured exactly as a DT, but which simulates and emulates the physical environment only in a sufficient way and not in a complete and deep manner. With this specific simulation and emulation system, there is a relevant saving in computing time and effort, even if the results will be less reliable than the ones provided by a DT. A Digital Shadow could be a key enabler in order to act as a transition from CPS to DT (Tseng *et al.*, 2019).

Table 2 summarises the enablers to DT implementation identified in the literature, as well as the barrers solved by them.

Technological Enablers		
Enabler	*References*	*Barrier/s solved*
Development of a structured information model	Lu *et al.*, 2020	
Development of a communication network	Negri, Fumagalli and Macchi, 2017; Lu *et al.*, 2020)	I
Development of a fully automated flow of data	Redelinghuys, Basson and Kruger, 2019	II
Development of a processing method for the analysis of the massive amount of data	Lu *et al.*, 2020	
Development of a proper decision-making structure	Redelinghuys, Basson and Kruger, 2019	
Develop a proper method for collecting data (e.g. CPSs)	Negri, Fumagalli and Macchi, 2017; Urbina Coronado *et al.*, 2018; Cohen *et al.*, 2019; Redelinghuys, Basson and Kruger, 2019; Wang and Wang, 2019	II
Development of a proper information repository	Redelinghuys, Basson and Kruger, 2019	
Development of a a semantic data model	Negri, Fumagalli and Macchi, 2017	

Development of a simulation and emulation system	Redelinghuys, Basson and Kruger, 2019	
Development of a simulation and emulation framework	Negri, Fumagalli and Macchi, 2017	
Development of a *Digital Shadow*	Tseng *et al.*, 2019	

Table 2: Enablers Categories

4.Discussion and Future research directions

From the analysis of the literature, technological and knowledge barriers and enablers have been identified and categorised. While the technological component is widely discussed in the literature both as barriers and enablers, the knowledge-related component is covered only as a barrier-related theme. Moreover, even with regards to the technological component, not all the barriers are solved by enablers. Therefore, there is the need for further studies aimed at filling this gap.

However, managerial barriers and enablers are rarely discussed in the scientific literature. Nonetheless, these have been underlined by several recent professional reports for practitioners. Thus, the elements of these categories have been deductively developed from those reports (McKinsey, 2018; Mussomeli et al., 2018; ARUP, 2019; Deutsche Post DHL Group, 2019).

Managerial Barriers. The barriers belonging to this category are threefold. Firstly, companies find difficulties in creating enough value from the DT. As a matter of fact, companies find often challenging to create enough value from a technogical transformation in digital manufacturing and it is hard to justify the resources involved, as cost, time and management efforts (McKinsey, 2018). Secondly, there is a relevant need for a change in managers' mindset and roles. In order to drive the fast digital transformation towards digital twins-enabled operations, the entire company should try to flatten hierarchies. Managers should try to encourage teams and allow sometimes errors from their staff. In addition, an efficient digital transformation implies that managers should be able to collaborate and communicate with all the units of the company. Commitment and collaboration within the company, and most of all from managers, is needed in order to develop a successful DT implementation process. The challenge is to train managers in developing more sophisticated soft-skills that can allow them to switch roles effectively with the situations (Mussomeli *et al.*, 2018; Deutsche Post DHL Group, 2019). Finally, a general cultural change is needed to develop a successful DT implementation process. The digital twins are disruptive technologies and therefore there is the need of a delicate process of change management, both for generational and habit factors (ARUP, 2019; Manca, Grugni and Mirzazadeh, 2019).

Managerial Enablers. As for the managerial barriers, also managerial enablers are threefold. The first enabler is to strategise the transformation process. As a matter of fact, a company first needs to check which will be the benefits to the pain points at the operational level and if the improvements will generate a competitive advantage. A roadmap can help reduce the lack of vision and provide clear steps to reach the desired results. The innovation process of infrastructures is the second enabler. Indeed, a company's infrastructure should be comprehensive, scalable, analytics-enabled, integrated and secure. In addition, it would be useful to minimise the overall complexity of the architecture, to find external partnerships and to ensure an agile execution across the company's functions. Finally, the last enabler is to mobilise the organisation, as the digital transformation must be driven from the top level of the company (McKinsey, 2018).

Furthermore, an interesting future research path would be to find what are the antecedents to both the technological and the managerial enablers. Moreover, assessing the current state of the availment of the main enablers in companies could lead to the study and identification of the main challenges that a company could face when developing an enabler to the DT.

Table 3 summarises the managerial barriers and the managerial enablers, as well as the barriers solved by the enablers.

Managerial Barriers		
Barrier	*References*	*Barrer ID*
Hard to determinate the return on investment	McKinsey, 2018	VII
Need for a change in managers' mindset and roles	Mussomeli *et al.*, 2018; Deutsche Post DHL Group, 2019	VIII
Need for a general cultural change	ARUP, 2019; Manca, Grugni and Mirzazadeh, 2019	IX
Managerials Enablers		
Enabler	*References*	*Barrier/s solved*
Strategise the transformation process	McKinsey, 2018	VII
Innovate the infrastructures	McKinsey, 2018	VII
Mobilise the organisation	McKinsey, 2018	VII

Table 3: Managerial Barriers and Enablers

5.Conclusions

This paper proposes a systematic literature review about the main barriers and enablers to DT implementation, with particular attention given at the challenges for SMEs.

Barriers had been categorised as technological or knowledge-related, even if the former category seems to be by far the most studied one. As a matter of fact, the technological component of DTs represents a critical issue in order to achieve a successful implementation, especially for SMEs. As for the technological component, also the knowledge-related one is particularly relevant for SMEs, as these companies may lack of the internal skills and expertise needed to build and run a DT.

On the other hand, in the literature enablers have been found related only to a technological component. The main tools proposed in this paper could help companies to reach the level of automation and accuracy in the real-time data exchange, storage and processing required to develop a successful and efficient DT. Finally, an interesting alternative of the DT to provide remarkable savings of computional effort and time is proposed in the form of a Digital Shadow simulation model.

Furthermore, this paper provides future research paths highlighting the need of a deeper analysis on the managerial barriers and enablers to DT implementation. As a matter of fact, in the literature the managerial aspects of a DT implemention process is rarely discussed. From the analysis of several professional reports (McKinsey, 2018; Mussomeli *et al.*, 2018; ARUP, 2019; Deutsche Post DHL Group, 2019; Manca, Grugni and Mirzazadeh, 2019), some managerial enablers and barriers have been dedudictevely developed.

However, the research process on the theme of the DT and especially on the managerials enablers and barriers to a successful DT implementation is still at its infancy and therefore there is a relevant need for further studies on this topic. Furthermore, since the core topic of this paper is a quite recent one, the research process should be enlarged in order to include also conference publications which could provide interesting and relevant contributions to this literature review. Moreover, another limitation of this paper is related to the choice of including in the search process only papers strongly connected with the topic of Industry 4.0.

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