POLITECNICO DI MILANO

School of Industrial and Information Engineering

Master of Science in Management Engineering

Technologies of Industry 4.0 and the impact on the New Generation of Manufacturing Execution System: A Systematic Literature Review

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To my beloved family,
my parents Francisco and Malena,
my sibling Pau, for their
unconditional love and emotional
support in this challenge.

Contents

Abstract (Italian)

Con l’avvento dell’Industria 4.0 e il suo enorme impatto sull'industria manifatturiera, è importante capire come le aziende si stiano adattando a questa rivoluzione e, quali decisioni strategiche e metodologie dovrebbero applicare. Negli ultimi anni, si è verificato un incremento della ricerca sull’argomento, per assistere le aziende nell’affrontare queste nuove sfide che richiedono spesso cospicui investimenti e comportano modifiche strutturali, anche data la necessità di migrazione verso questo nuovo paradigma. C’è una maggiore consapevolezza sul tema del Manufacturing Execution System (MES) e il suo rapporto con l'Industria 4.0, poiché si tratta di un'area inesplorata, in cui la necessità di ricerca è quindi più marcata. Dato che, il MES è il centro dei sistemi di produzione nella maggior parte delle aziende manifatturiere, è importante capire come sta cambiando il nuovo paradigma dell'Industria 4.0 e come il MES debba essere adattato per soddisfare le nuove esigenze del settore.

In questo documento, questo argomento viene presentato per comprendere meglio la nuova relazione tra l’Industria 4.0 e MES. Nella Sezione II viene presentata una definizione dettagliata di ogni termine e la relativa lacuna da coprire. Nella Sezione III, si descrive la metodologia di ricerca e l'obiettivo della ricerca. Le Sezioni IV, V e VI forniscono risposte all'obiettivo di ricerca spiegando in dettaglio l'impatto sul MES causato dalle nuove esigenze del settore date dall'Industria 4.0. Infine, la Sezione VII, trae le conclusioni e i risultati, con cui si determina che il MES tradizionale è stato rimodellato da diverse tecnologie dell'Industria 4.0, e fornisce approfondimenti tecnici per comprendere l'importanza di queste tecnologie e la loro corretta implementazione al fine di una migrazione verso l'Industria 4.0.

Abstract

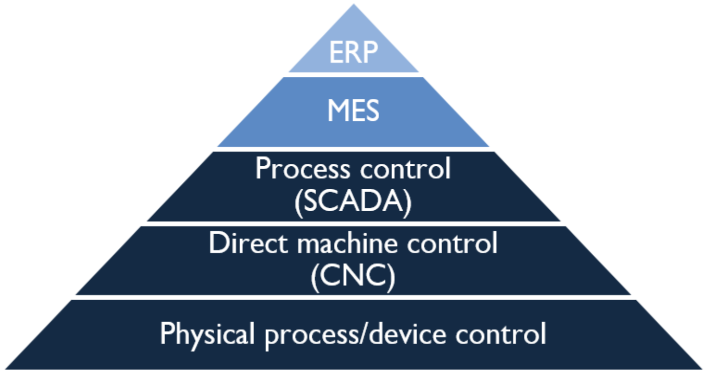
With the advent of Industry 4.0 and its enormous impact on the manufacturing industry, it is important to understand how enterprises are adapting to this revolution and, which strategic decisions and methodologies could be implemented. Recently, there has been increasing research on this topic, helping to understand how to cope with these new challenges that often require a significant investment involving structural changes. It is imminent that companies migrate to this new trend to survive. There has been an increased awareness on the topic of Manufacturing Execution System (MES) and its relationship with Industry 4.0 since it is an area yet to be explored, where a lot of research must be done. As MES is at the core of the manufacturing systems in most enterprises, it is relevant to understand how the new paradigm of Industry 4.0 is evolving and how MES must be adapted to attend to the new requirements of the industry.

In this work, this topic is presented to better understand this new relationship within Industry 4.0 and MES. In Section II, a detailed definition of each term is presented as well as the gap to be covered. Section III describes the research methodology and the research objective. Sections IV, V, and VI provide answers to the research objective explaining in detailed the impact on MES caused by the new requirements of the industry base on Industry 4.0. Finally, Section VII draws the conclusions and findings, where it is determined that the traditional MES has been reshaped by different Industry 4.0 technologies and provides insights for practitioners to understand the importance of these technologies and their right implementation to transition to Industry 4.0.

Keywords: *Manufacturing Execution System* • *Industry 4.0* • *Technologies of Industry 4.0* • *Automation Pyramid* • *Systematic Literature Review*

Executive Summary

Industry 4.0 offers an unprecedented opportunity for transformational success, based on its decentralized vision, autonomous networks, and smart products, it is the direction manufacturing industries must move to achieve intelligence, resource efficiency, and high-performance. Starting from the first industrial revolution characterized by water and steam power resulting in revolutionary mechanical production facilities, the second industrial revolution with the development of electronic and Information Technology (IT) systems, and the third industrial revolution, a century later, with the automation production, changing the way manufacturing was developed. 30 years later the society is living a new revolution, characterized by the internet, big data, networks, and connectivity. The Reference Architectural Model Industry 4.0 (RAMI4.0) has been born because of the importance and complex structural changes companies must do at all levels to adapt to the requirements of Industry 4.0. Based on a service-oriented architecture the new standard proposed a reference model for companies to migrate efficiently and to implement it accordingly. Society is living a huge revolution in the industry; the new technologies emerging are moving the way currently products are manufacture and providing services. Particularly in the manufacturing environment, the classic automation pyramid (*Figure A*). has now been impacted by the phenomena. New researches on this topic have shown that the well-defined hierarchical model is moving in the opposite direction. Each level is now affected by the revolution. From the field level, the control system, Manufacturing Execution Systems (MES), and up to Enterprise Resource Planning (ERP) level, it is seen an unprecedented evolution.



(Figure A). Classic Automation Pyramid

Starting from the understanding of what Industry 4.0 is and the awareness of how is changing everything, particularly focusing on the automation pyramid, a gap has been observed that will be cover by this paper, is to know specifically "how" Industry 4.0 is reshaping it. This work is exclusively centralized on the operation level represented by the MES. Because of the importance of MES in the industry and the important upcoming challenges companies will have, this paper wants to go deep and cover the gap to know how the MES is changing and will be changed by Industry 4.0.

The methodology chosen was based on a general research question divided by two sub-questions, one focused on the technologies of Industry 4.0 and the other one the characteristics of the technologies, this last one to have a clearer idea on the "how". A systematic literature review was done by a discrimination process taking at the end 46 articles related to MES, Industry 4.0 technologies, and any strong relationship between the two terms.

Bibliographic network analysis is done for a broader perspective about the meta-data fed by the papers selected. Two analyses were selected one with the keywords and the other about the reference by countries. On the first analysis, the most representative keywords were regarding, Industry 4.0, Cyber-Physical System (CPS), Internet of Things (IoT), Optimization, Information management, and scheduling. From a time-span perspective, the oldest keywords were based on information services, industrial economics, automation, and real-time up to the newest including Artificial Intelligence (AI) applications, digitalization, CPS, IoT, and market requirements. The second analysis presents a strong reference from China, Sweden, Germany, among other countries. Interesting to conclude that currently the Nordic countries and Germany are the ones that are having more references in these late years. This conclusion adding the results of the keyword analysis reveals that Industry 4.0 technologies are having a high interest in research on developed countries.

As stated before, the first part of the framework was to execute a literature review to know which are the most relevant technologies of I4.0 that are impacting MES. The results show a total of seven technologies (*Table A*):

Internet of Things (IoT)	Artificial Intelligence (Chatbots) (AI)
Radio Frequency Identification (RFID)	Digital Twin (DT)
Cyber-Physical Systems (CPS)	Additive Manufacturing (AM)
Cloud Computing (CC)	

(Table A). Industry 4.0 Technologies

been CPS, IoT, CC, and RFID the most relevant. RFID is the oldest one and not part of I4.0 but is taking a high relevance because of its potential to interact with other I4.0 technologies and provide real-time information and CPS. The second part of the framework was focus on a literature review to know which characteristics are the most representative and relevant to different technologies. The purpose of this was to know exactly the way the technologies are impacting MES. The results gave a total of eleven characteristics (Modularity, Integrability, Diagnosability, Convertibility, Scalability, Customization, Decentralization, Service orientation, Interoperability, Real-time capability, and Virtualization). From this list, an analysis on MES was done primarily to understand which characteristic the industrial community requires MES to have. The results were an MES capable to integrate distinct functions, being decentralized, being able to obtain real-time information, and being modular. These results show an interesting reflection on what is expected of the new generation of MES. Moving forward with the characteristic analysis, a clustering method is done to match the technologies with the characteristics. The literature review showed that CPS is the technology more complete in terms of characteristics it has, the most representative ones are Real-time capability and Integrability with five and four technologies having, respectively.

In the last section of the framework presented, each technology is explained in a more detailed way to highlight through the characteristics they have how they impact MES.

- *IoT*: A device that can be connected to the internet allowing two-way communication across or between shopfloor (Isaksson, A. J., Harjunkoski, I. & Sand, G., 2018), impacting on MES through Interoperability and Real-time capability.
- *CPS*: Multidimensional systems that can integrate the cyber world with the physical world (Tao *et al.*, 2019). It impacts MES through Modularity, Decentralization, Interoperability, Virtualization, Real-time capability, and Integrability.

- *Cloud Computing*: An emerging model enabling computational resources through services to final users (Alexakos, C. and Kalogeras, *A.*,2017), impacting on MES through Integration and Service orientation
- *Artificial Intelligence*: A system's ability to interpret external data correctly, to learn from such data, and to use those learnings to achieve specific goals and tasks through flexible adaptation (Haenlein and Kaplan, 2019). It impacts MES through Real-time capability
- *Digital Twin*: Type of simulation creating virtual models of the physical objects (Tao *et al.*, 2019), impacting on MES through Real-time capability, Interoperability, Diagnosability, and Virtualization
- *RFID*: Digital data encoded on tags/labels to be captured by a reader via radio waves (Yang, Z. *et al.*, 2015). It impacts MES through Real-time capability
- *Additive Manufacturing*: Process to join materials by adding layer upon layer to make objects from a 3D model data (D'Antonio *et al.,* 2015), impacting on MES through Customization.

As seen above, the last part of the framework combines the three elements of our interest, MES, technologies of I.40, and the characteristics which represent the bridge between the other two mentioned. Having this information, a comparison between the traditional and the new generation of MES is done, from the traditional one we have an MES with a centralized structure, a strong integration with the business level (ERP), and the control lower levels like Supervisory Control and Data Acquisition (SCADA) and Programmable Logic Controller (PLC) where it provides some intelligence on the floor. In contrast with the new MES where you have a high digitalization, service-oriented and decentralized MES represented by a multi-agent perspective where MES is the broker in a CPS marketplace aiming to find the most efficient production solution.

There are several findings and conclusions about the framework presented, the first one is that MES is changing with the technologies of I4.0, some technologies are having a stronger impact on it. Digitization is capable to create a huge amount of data from the smart products that are essential in the execution of the new MES. This framework covers an important gap to understand about the evolution of MES, of high relevance for companies that are looking to migrate to Industry 4.0. Practitioners can rely on this information provided to understand how each technology works and what are the characteristics they have, to know what elements or what do companies need to do before investing in these technologies and be ready for the new revolution, as mentioned before, it, not an easy-going migration as it requires a vast number of resources and investments but at one point a necessary shift to survive in the new era of manufacturing.

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List of abbreviations

AI – Artificial Intelligence

AM – Additive Manufacturing

CC – Cloud Computing

CPPS - Cyber-Physical Production Systems

CPS - Cyber-Physical Systems

DFAM – Design for Additive Manufacturing

DT – Digital Twin

ERP – Enterprise Resource Planning

I4.0 – Industry 4.0

ICT - Information and communications technology

IoT – Internet of Things

IT - Information Technology

MES – Manufacturing Execution System

MESA - Manufacturing Enterprise Solutions Association

PLCs – Programmable Logic Controller

RAMI 4.0 - Reference Architectural Model Industry 4.0

RFID – Radio Frequency Identification

SCADAs – Supervisory Control and Data Acquisition

SCM – Supply Chain Management

SMEs – Small Medium Enterprises

WIP – Work in progress

I. Introduction

The new industrial revolution is here. With the constant changes in environmental conditions results from globalization, short innovation cycles, the increase of complexity of products, fierce competition among enterprises, new technologies, and the era of digitalization a new paradigm call *Industry 4.0* is changing the global manufacturing industry.

Enterprises and SMEs must be able to cope with this and firstly, understand the impact of it as it is reshaping different levels of automation pyramid and secondly the key elements to be done to migrate, in terms of resources to use, investment to be done, reconfiguration on the management process and even strategy corporation goals and business models.

Non an easy task ahead for companies to adapt to the new industrial requirements but strongly suggested to be highly informed about the transition process, tools and to rethink and take an active strategy move to migrate in the fastest and most accurate way to take business advantages against others.

II. Background

Firstly, to understand what Industry 4.0 means in all its ambit, the first step is to understand how the term was created. The first time the concept was released was in 2011 at the Hannover Fair in Hannover, Germany. It was promoted by the German government as a strategy to promote computerization in manufacturing. Since then, the concept has been of high interest among the industrial community with high investment in research. Industry 4.0 aims at exploiting the high innovation and economic potential resulting from the continuing impact of rapid Information and communications technology (ICT) in the industry (Demartini *et al.*, 2017). To understand the size of the impact of this new revolution is important to go to the past and have a reference on the evolution of the manufacturing industry the reason Industry 4.0 is called like that and why is to be called the fourth revolution in manufacturing.

The first industrial revolution appeared around 1784, after the introduction of mechanical production facilities with the help of water and steam power, manual work was replaced by the industrial factory. The first historical movement where the man allowed himself to possess new progress in production development due to technology and science.

The introduction of division of labor and mass production with the help of electrical and oil energy was the main characteristic of the second industrial revolution that appeared around 1870. The qualitative scientific knowledge and technological innovation lead to the discovery of new energy sources and materials replacing the well-known steam engines.

The third industrial revolution appeared 100 years later in 1970 characterized by the development of automation, computers, and electronics. This revolution represents the start of the shift from analog electronic to digital electronic. PLCs and more developed robots appeared at this time reshaping the way manufacturing was done.

40 years later, Industry 4.0 represents the fourth industrial revolution (Kainer, 2017). Noticeable to point out that this last revolution did not appear 100 years later as the other ones, this due to the among of technology, data, and knowledge humans have been capable to develop. *Figure 1* illustrates a summarized timeline.

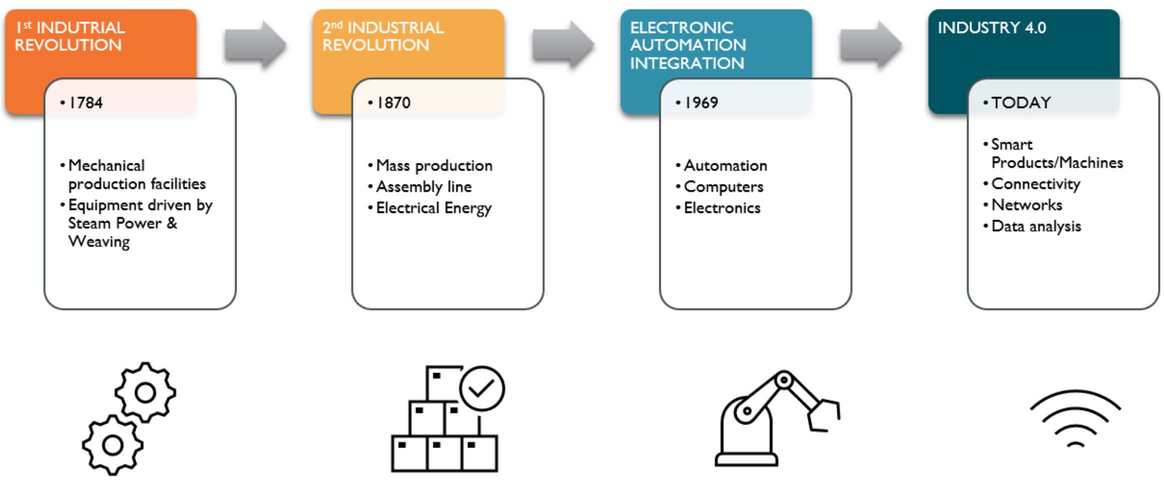

Figure 1. Industrial Revolutions

Industry 4.0 is a comprehensive transformation of industrial production through digital technology. It helps with current challenges to be more flexible and react to changes in the market easier. Its base is developed on IT and connectivity (internet) among devices and networks. Industry 4.0 is a new paradigm that at nine years since the concept arrived currently is transforming the industry in different sectors. As the authors Daniel Schulte and Armando Colombo have defined, this new trend is supported by new disruptive combination, communication, control, and mechatronics technology-driven approaches in traditional industrial systems and as an industrial competition of business/services processes.

Until now, the decision-making criteria was the quality of the product. That was the objective of the industry as the key element to survive and be competitive. Nowadays, the customer pays more attention to the quality of service including product customization, flexibility, schedule accuracy, and delivery time. All these new requirements of the market have pushed to the creation of a basic set of specifications for digitalizing the industrial systems to cope with the competition. The RAMI 4.0 is the first and currently the only standard that enables companies to evolve to Industry 4.0 requirements. RAMI4.0 propose using state-of-the-art ICT to support structural reconfigurability and evolvability of industrial systems, also aiming to make the industrial process more controllable and manageable in real-time operational condition when emergent behaviors arise (Schulte, D., & Colombo, A. W. 2017).

The RAMI 4.0 based on a service-oriented architecture is structured as a three-dimensional map (*Figure* 2), it breaks down complex processes into handle packages. In one axis the architecture is formed by six layers with a hierarchical control order from the asset layer up to the business layer. The second axis is composed of the Life cycle & value stream which includes Type Development, Type Maintenance, Instance Production, and Instance Maintenance. This axis represents the development of the product and its respective phases. The third axis is composed of the Hierarchy levels which reflects the concept of functional separation of cyber-physical systems. This hierarchical model is laid down in the computer-integrated manufacturing model and the Batch Control Model IEC62264 and IEC61512 respectively (Binder, 2017). This reference is a migration process to an approach in the most optimal way on how to adapt the company to the new environment, taking for a granted different set of technical, infrastructural, organizational challenges.

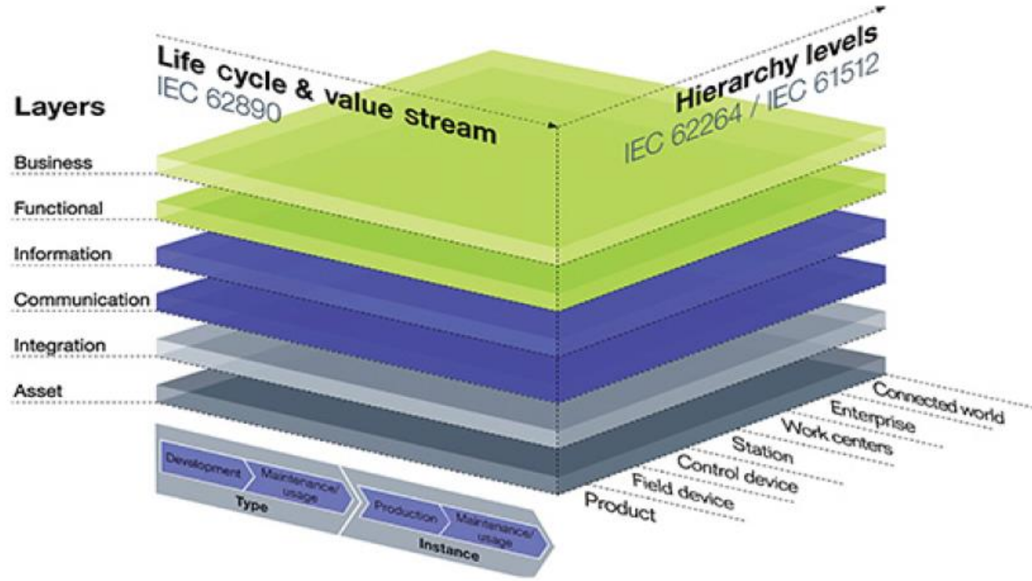

Figure 2. RAMI 4.0

With the recent developments and emerging technologies, is expected that devices and systems can seamlessly communicate, becoming more integrated and collaborative supported by the IT structures. Directly impacting on the process control and operations process; reshaping what is known as the traditional automation pyramid, structurally separating, and modifying each level (scheduling, planning, controlling, etc.). Industry 4.0 and its technologies are enabling to overcome hierarchy. To better illustrate this evolution, the authors Isaksson & Harjunkoski have illustrated it (*Figure 3*), showing the traditional and the new automation pyramid. This reference can be strongly related to the standard IEC 61499 (Thrombolite's, 2013) which represents a component solution for distributed industrial automation systems. Waschull & Wortmann proposed another architecture focusing on the top layer of the traditional pyramid (*Figure 4)*. Where they emphasize decentralized control and strong interoperability among the systems. This work will only focus exclusively on the layer of the *Manufacturing Execution System* (MES) and its relation to Industry 4.0 without including any other layer of the automation pyramid.

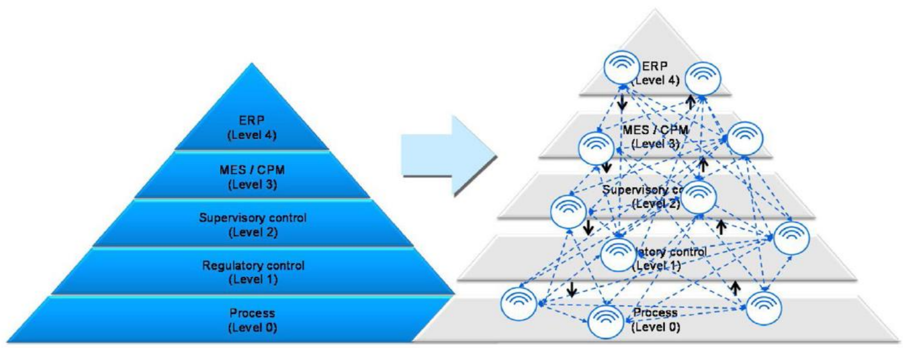

Figure 3. Automations Pyramids (Isaksson & Harjunkoski)

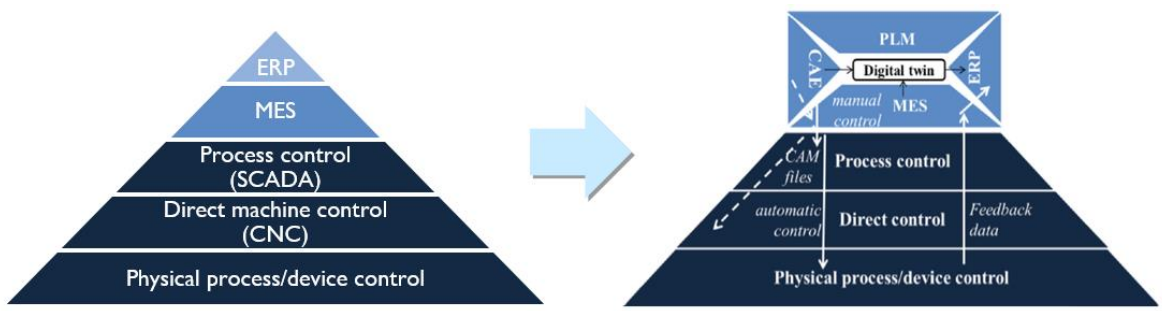

Figure 4. Automations Pyramids (Waschull & Wortman)

For more than decades, manufacturing companies have invested in computer systems to help run their operations. The first systems were customized according to the needs of the manufacturer's operating style. Due to this, commercial software products started to gain market share developing what is call now Manufacturing Execution Systems (MES). MES has been present since 1990, been related to different standards (e.g., IEC 62264, ISA-95).

Today, MES has become very popular in the integration of manufacturing planning and control tasks, to deal with data to decrease cost, increase quality and meet efficiency requirements, it has been implemented in shop floors for different industries for decades.

According to MESA, MES deliver information that enables the optimization of production activities from order launch to finished goods, guides initiate, responds to, and reports on plant activities as they occur. It focuses on the digitalization of shop floor activities to monitor, document, and report information on the transformation of raw materials into finished goods in an integrated manner, enabling the control and optimization of production processes in near-real-time (Waschull *et al.*, 2018).

One of the main advantages of MES is the ability to feed information and communicate with other types of systems the following table (*Table 1*) summarize the 2-way interactions:

System	From MES to other systems	From other systems to MES
ERP	Information regarding costs, cycle times, throughput, and other performance data.	Plans some of the work.
SCM	Data about order status, production capacities, and capabilities.	Mater plans and schedules to timing activities in the plant.
Sales and Service Management	Links to provided information to success in quoting and delivering according to what happens on the facilities.	Configurations and quotes for the baseline of order information for production.

Product and Process Engineering	Data for product yield and quality measurements.	Work instructions, recipes, and operational parameters.
Controls	Recipe and instructions downloaded that reflect how to run the production optimally.	Measure actual performance and operating conditions as they change in the process.

Table 1. MES In the Information Systems Architecture

In *Table 2* MES functions are presented (Lee, Nam, and Lee, 2012) to highlight the different areas where MES can control and provide information:

Operations scheduling	Sequence and timing activities for optimized plan performance based on resources.
Document Control	Managing and distributing information on products, processes, or orders, as well as gathering certification statements of work and conditions.
Resource Allocation	Guide what people, machines, tools, and materials should do, and tracking what they are currently or have just done.
Performance Analysis	Comparing measured results in the plant to goals and metrics set by the corporation/customers.
Process Management	Directing the flow of work in the plant-based on planned and actual production activities.
Quality Management	Recording, tracking, and analyzing product and process characteristics according to specifications.

Data Collection/Acquisition	Monitoring, gathering, and organizing data about the process, materials, and operations from the resources (People, Machine, etc.).
Maintenance Management	Planning and executing appropriate activities to keep equipment and other capital assets in the plant performing to a goal.
Labor Management	Tracking and directing the use of operations personnel based on qualifications, work patterns, and business needs.
Product Tracking and Genealogy	Monitoring the progress of units, batches, or lots of output to create a full history of the product.
Dispatching Production Units	Giving the command to send materials or orders to certain parts of the plant to begin a process or step.

Table 2. MES Functions

The tables presented show the capabilities and the extended boundaries where MES can cope. This informatic system aims to provide enterprises benefits and advantages when it comes to controlling the production floor. And why through decades has been a key asset for companies to cope with industry requirements. *Figure 5* presents a model illustrating the connections among the functions and the interaction with other systems.

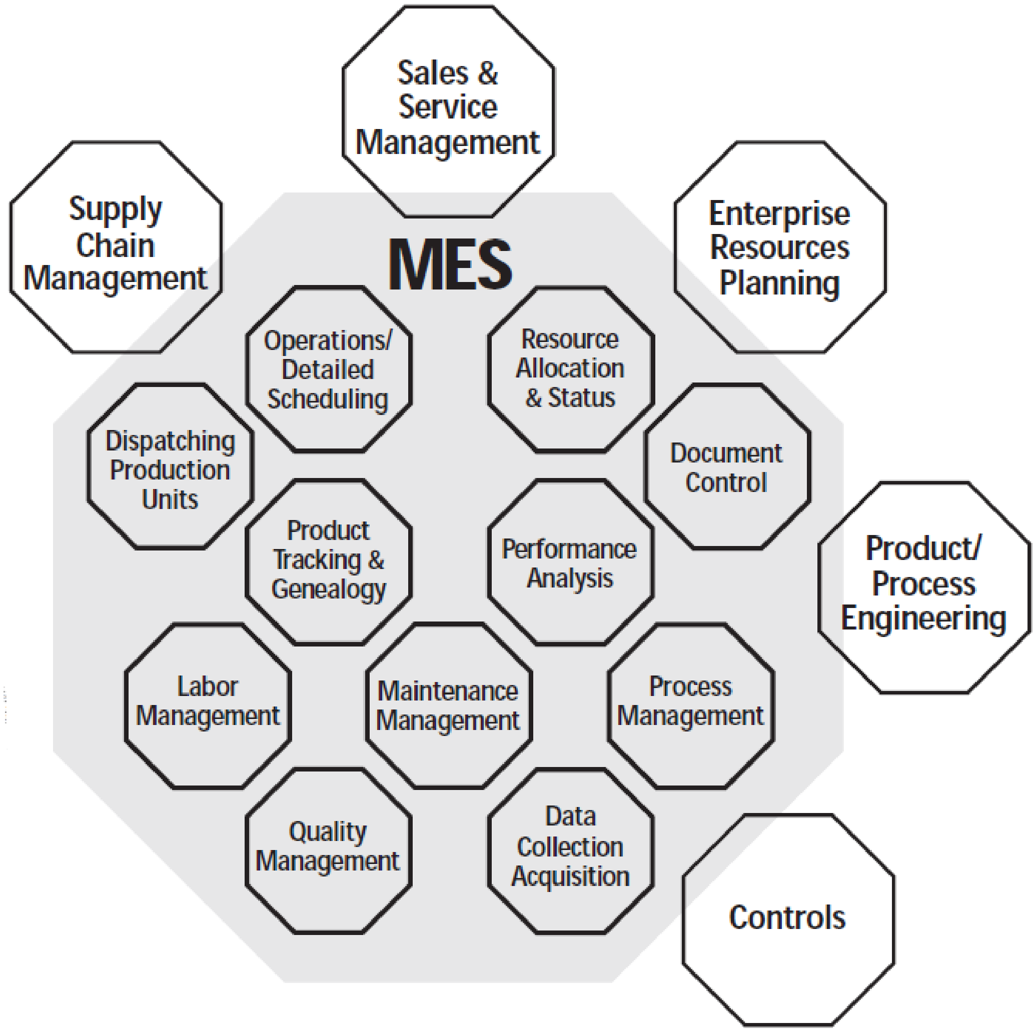

Figure 5. MES Functional Model (Lee, Nam, and Lee)

As already discussed in the traditional automation pyramid, MES was positioned as an integration technology to bridge the production floor with higher business levels (e.g., ERP). It was the eyes of the management departments to see what was happening on the lower layer and in the production in general. It was perceived as an integrated decision support system, giving a general view of all resources involved. The current focus seems to be on the digitalization of the shop floor activities, to collect, analyze and exchange real-time information. So MES is having a greater role in smart factories than just providing features and information for manufacturing management.

Understanding what is MES and the strong role it has on the industry and understanding what Industry 4.0 and the impact it is having on industries, the next step is to highlight how these two terms are related, how are they reshaping between them in this new era soaked on digitalization and technologies never seen before. It is clear the gap to be fulfilled, and the importance to answer how MES is changing with Industry 4.0 that is already here. How through the technologies emerging with digitalization they are reshaping what is known as MES.

III. Methodology

i. Research Gaps and Objectives

As mentioned before there is a strong interest to understand how Industry 4.0 is changing the industry and will be of it in the future with the new technologies that are appearing. But which are these technologies? What peculiarities and characteristics do these technologies have that are reshaping the future as society knows it? Are there any connections, similarities between these technologies? How diverse they are between them? Could there be a particularity among them that could lead us to understand better Industry 4.0? And what connection do these particularities could have with MES? Is MES capable to sustain and adapt itself to the structures and configuration of these technologies? In this sense, this paper proposes a framework to answer all these questions to deeply understand how this phenomenon is impacting MES. There has not been a strong literature review on this relationship between MES and the technologies of Industry 4.0, reason why the main object research to cover is:

Q1 How these new enabling technologies in Industry 4.0 (such as RFID, Cloud Computing, IoT, Additive Manufacturing, etc….) are changing the MES to support the manufacturing industry?

Moving forward to understand more deeply the main objective, two sub-objective research questions are developed:

Q1.a) What are the enabling technologies of Industry 4.0?

Q1.b) What are the characteristics of these technologies?

These sub-objective questions aim to have a more understanding of what the literature says and to answer the "how is changing MES" of the main objective proposed.

ii. Research Steps

The methodology adopted was the following: first, a systematic literature review using the search engines of Google Scholar and Scopus, filtering by engineering and English articles. The first section of the literature review was using keywords like "Manufacturing Execution Systems, Industry 4.0, Digitalization and MES Evolution," this first section was filtered starting from 2005, as from this year more paperwork was done on these topics. Afterward, to understand any trend by years, the keyword used was "Manufacturing Execution System," filter by year in the following way: 2010-2011, 2012-2013, etc.

Secondly, the chosen articles were filtered by their relevant content based on general information about MES, advantages of I4.0 technologies in the industry, and changes/evolution on MES, totally enlisting 74 articles.

Finally, a filter was gone again to exclude articles where the relationship between technologies and MES was not strong enough or does not provide a clear impact on MES, totally enlisting 46 articles. *Figure 6* represents a flowchart of the systematic literature review.

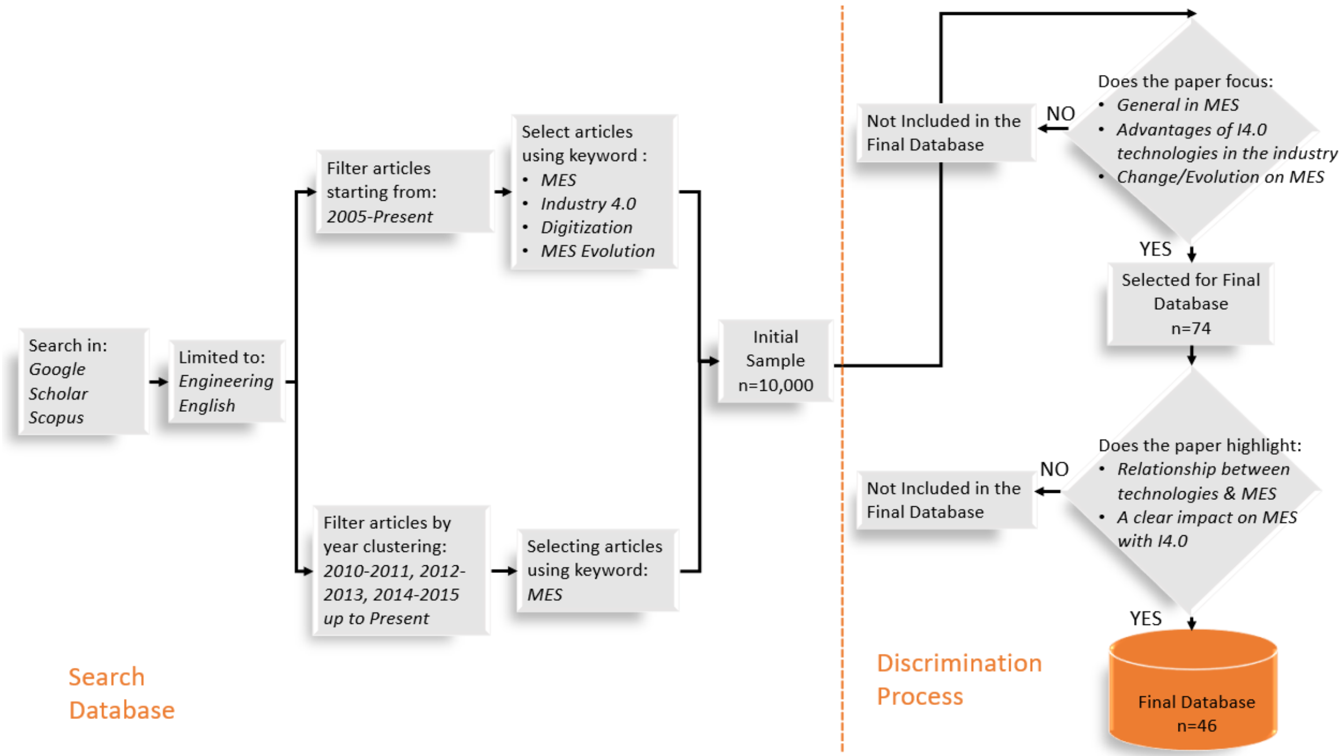

Figure 6. Systematic Literature Review Flowchart

iii. Bibliographic network analysis

Based on the literature review done, to understand more in deep and to have a broader perspective a biometric analysis was done. The VOS viewer program was used for this proposal as its approach is based on grouping and bibliometric mapping of the information provided, allowing visualization of similarities in diverse ways. Two analyses were chosen the first one was based on keywords analysis. *Figure 7* shows the visual results and *Table 3* lists the keywords by clusters. The type of analysis selected was co-occurrence (based on the number of documents in which they occur together), with keywords as the unit of analysis. The threshold selected was two as the minimum number of occurrences of a keyword reducing from 385 keywords to 65. From *Figure 7* it can observe the strongest keywords were MES, Industry 4.0, Optimization, IoT, Information Management, and Embedded system. There is a trend in time about the keyword network was around 2014, automation, scheduling, information services, RFID, ERP, and real-time were the most representative keywords going to the most recent ones dominated by IoT, CPS, digitalization, market requirements, Industry 4.0, artificial intelligent application, and embedded systems. This trend shows us how Industry 4.0 is having a strong impact on the literature research and is moving towards a new evolution in the industry.

Cluster 1		**Cluster 2**	
Data collection	MES	AI applications	Intelligent manufacturing
ERP	Optimization	ERP	Multi-agent systems
Industrial economics	RFID	Information management	Production control
Industrial management	Real-time	Information systems	WIP
Information services	Shoop floor	Information Use	
Cluster 3		**Cluster 4**	
Automation	Digital twin	CPS	Market Requirements
Big Data	Physical systems	Digitalization	Planning
Decision support systems	Supply chains	Embedded systems	Scheduling
Integration	Vertical integration	IoT	Smart Factory
Industry 4.0		Life cycle	

Table 3. Biometric Keyword Clustering

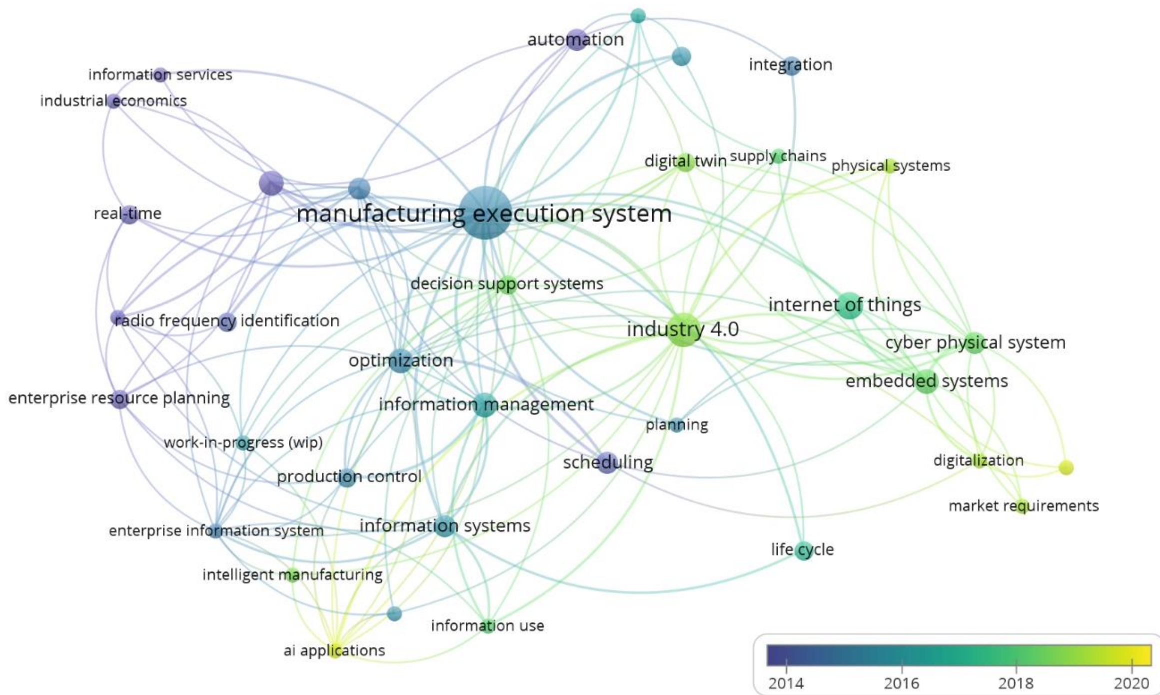

Figure 7. Keywords Bibliometric Analysis

The second analysis was done by country. *Figure 8* shows the visual results. The type of analysis selected was bibliographic coupling (based on the number of references they share), with countries as a unit of analysis. The threshold selected was one as the minimum number of documents of a country having 20 countries, 20 achieving the threshold. *Figure 8* shows that China, Sweden, Singapore, Hong Kong, Germany, Italy, and Denmark have the strongest link on references. From a timeline perspective (oldest to newest) Hong Kong, Austria and Rumania are the countries that used to have more relevance in terms of references to the scientific community. Currently, Germany, Sweden, and Denmark are the ones that show a stronger link. This could be interpreted as now with Industry 4.0 these countries are having a strong research investment on the topic.

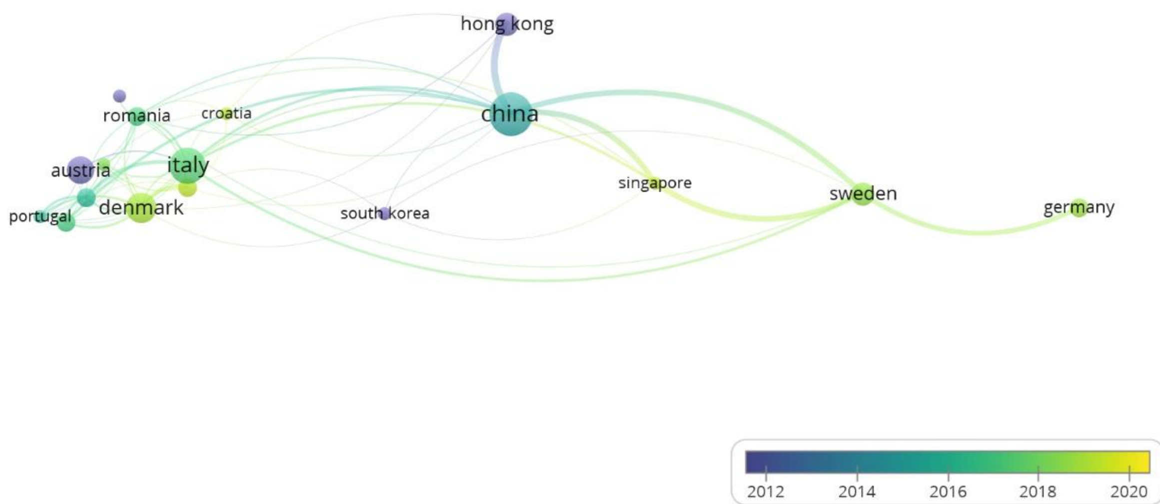

Figure 8. Country Bibliometric Analysis

Based on the literature review and the bibliometric analysis presented above, the framework proposed will be divided into three main sections. Section IV will be highlighting the I4.0 technologies and the relevance of them in the literature review answers to the research question: *What are the enabling technologies of Industry 4.0?*

Section V will be on characteristics these technologies have, the relevance, relation among each one, and the relationship with the technologies answering to *What are the characteristics of these technologies?*

Section VI will go deeper into each technology found in Section IV supported in some cases by some industrial successful stories and explain through the most representative characteristics in each technology discussed in Section V how they impact MES.

Finally, Section VII will expose a comparison between the traditional MES and the new generation of MES.

IV. Industry 4.0 technologies

Based on the systematic literature review according to the corresponding filters, a total of 46 articles were selected. This research primarily aimed to find out technologies that are related to the I4.0 and have an impact on MES. Several technologies were found out (*Table 4*), but for simplicity only the most relevant technologies were selected, particularly RFID and IoT are considered as independent technologies in this analysis to highlight how these two terms have appeared in a different period and to explain each one from a different perspective even do several authors considered RFID as part of IoT as both can provide real-time information to upper-level information.

Internet of Things (IoT)	Artificial Intelligence (Chatbots) (AI)
Radio Frequency Identification (RFID)	Digital Twin (DT)
Cyber-Physical Systems (CPS)	Additive Manufacturing (AM)
Cloud Computing (CC)	

Table 4. Industry 4.0 Technologies

The following flow chart (*Figure 9*) synthesizes the results of the literature review, highlighting two main groups in terms of relevance. The first one is the technologies that had less relevance includes Digital Twin, Artificial Intelligence, and Additive Manufacturing. The other group is composed of Cloud Computing, CPS, IoT, and RFID, this last one is characterized by technologies that in the literature review showed more relevance and interest from the scientific community. The first hint on this review, emphasizes the relevance of CPS with MES, this is supported by "backbone for new MES"

(Filipov and Vasilev, 2016) and the relevance of IoT and Cloud computing. Les information regarding Additive Manufacturing is shown, this supported by the fact that is an emerging technology that is becoming a trend, but it still has few studies on it.

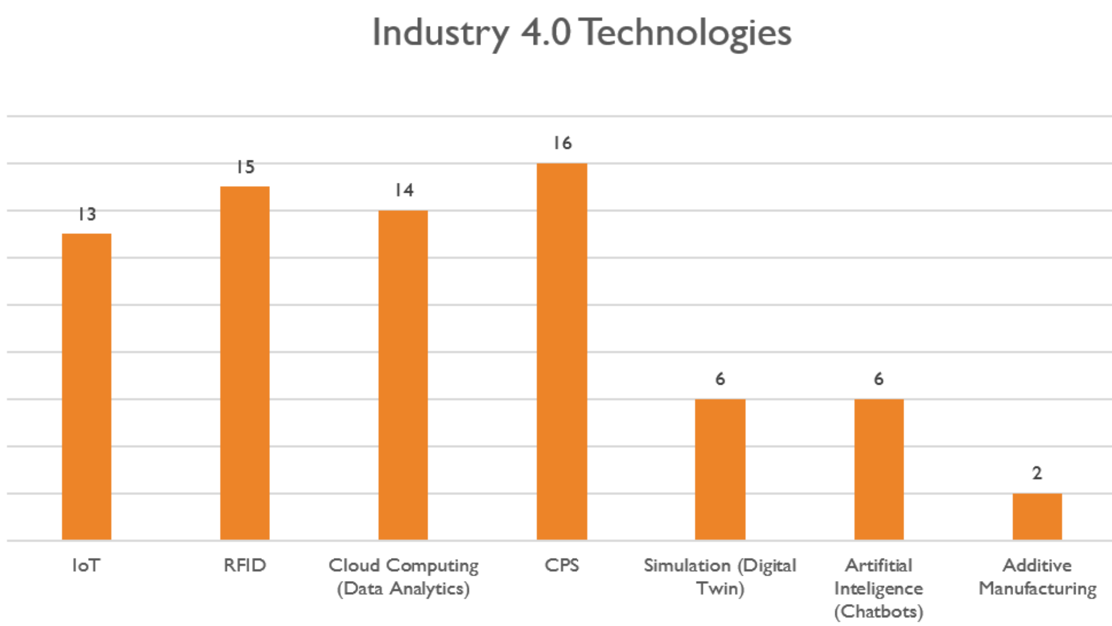

Figure 9. Industry 4.0 Technologies

A detailed representation was done through a matrix (*Table 5*) to understand and to visualize in another way the relevance of each technology according to a spam time from 2007 to 2020. It provides a visual representation of each technology on the X-axis and time on Y-axis. The literature shows how before 2010 MES focused on decentralization and investment in automation. Between 2010 to 2014 while keeping the decentralization structure they show a change in the evolution of MES aiming to create an MES more capable of showing more reliable information by reaching real-time information, this is also supported by how RFID technology has been present in the literature in those years as this is pure real-time technology. From 2015 till now, it can be highlighting how the new technologies of the I4.0

start to have relevance in the literature exploiting the new paradigm to change the way MES operates.

Year	Papers	IoT	RFID	Cloud Computing	CPS	Digital Twin	Artificial Intelligence	Additive Manufacturing
2020	A review on the characteristics of cyber-physical systems for the future smart factories			X	X	X		
2020	User-Friendly MES Interfaces Recommendations for an AI-Based Chatbot Assistance in Industry 4.0 Shop Floors						X	
2019	Review of Digital Twin applications in manufacturing					X		
2019	Digital Twins and Cyber-Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison				X	X		
2019	An Overview of Next-generation Manufacturing Execution Systems How important is MES for I4.0	X		X	X	X		
2019	Multi-agent Manufacturing Execution System (MES) Concept, Architecture & ML Algorithm for a Smart Factory Case						X	
2019	Integration-and-testing-of-the-RFIDenabled-Smart-Factory-concept-within-the-Learning-Factory2019Procedia-ManufacturingOpen-Access		X					
2018	RFID Based Manufacturing Process of Cloud MES		X	X				
2018	The impact of digitalization on the future of control and operations	X		X				
2018	The role of Digital Information Models for Horizontal & Vertical Interaction in Intelligent Production	X		X	X			
2018	Smart CPS vertical integration overview and user story with a robot			X	X		X	
2018	Status-and-future-of-manufacturing-execution-systems2018	X	X					
2018	Workflow-management-for-edge-driven-manufacturing-systems2018				X			
2018	A-Conceptual-Model-for-Developing-a-Smart-Process-Control-System2018Procedia-CIRP				X			
2017	Industry 4.0 _The evolution of Business Models	X		X	X		X	
2017	The New MES. The backbone of Industry 4.0	X		X	X	X		
2017	RAMI 4.0 based digitalization on an industrial extrude system.				X			
2017	Horizontal and vertical integration, as a requirement for cyber-physical systems in the context of Industry 4.0		X		X			
2017	Exposing MES functionalities as an enabler for Cloud Manufacturing			X				
2017	PLM-MES integration to support Industry 4.0				X			

2017	Digitalization of Manufacturing Execution Systems the core technology for realizing.	X		X	X	X		X
2016	Manufacturing Operation Management - The smart backbone of Industry 4.0	X	X	X	X		X	
2016	A Vertical and Cyber-Physical Integration of Cognitive Robots in Manufacturing	X			X		X	
2016	The Industry 4.0 revolution and the future of Manufacturing Execution Systems (MES)	X	X	X	X			
2015	Manufacturing Execution System Present Situation and Development Trend Analysis	X	X	X				
2015	Research of Internet of Things applied to the manufacturing execution system.	X	X					
2015	A Proposal of Manufacturing Execution System Integration in Design for Additive Manufacturing							X
2014	Modeling of RFID-Enabled Real-time Manufacturing Execution System in Mixed-Model Assembly Lines		X					
2014	me: Virtualization aware manufacturing execution system			X				
2013	Real-time data-driven monitoring and optimization method for IoT-based sensible production process.	X	X					
2012	Real-time data acquisition system and HMI for MES		X					
2012	RFID-enabled real-time manufacturing execution system for mass-customization production		X					
2011	RFID-enabled Real-time Manufacturing Execution System for Discrete Manufacturing: Software Design and Implementation		X					
2011	A radio frequency identification-enabled real-time manufacturing execution system for one-of-a-kind production manufacturing: a case study in mold industry		X					
2009	Manufacturing execution system a literature review		X					

Table 5. Industry 4.0 Technologies according to literature

V. Technologies' characteristics

Going to a deeper analysis to understand more in detail how the technologies presented in Section IV impact MES. Research in the literature review was done to find which characteristics do technologies have that are more relevant in the literature, the following flow chart *Figure 10* synthesizes the results of the literature review. The chart highlights how *Integrability*, *Real-time capability* is the most relevant characteristic in the literature meaning they are essential for the new MES execution. Followed by *Modularity*, *Service orientation*, *Decentralization*, *Interoperability*, and *Virtualization*. Finally, the least relevant characteristics are represented by *Scalability*, *Diagnosability*, *Customization*, and *Convertibility*, this last one due to low relevance is not considered in the further analysis.

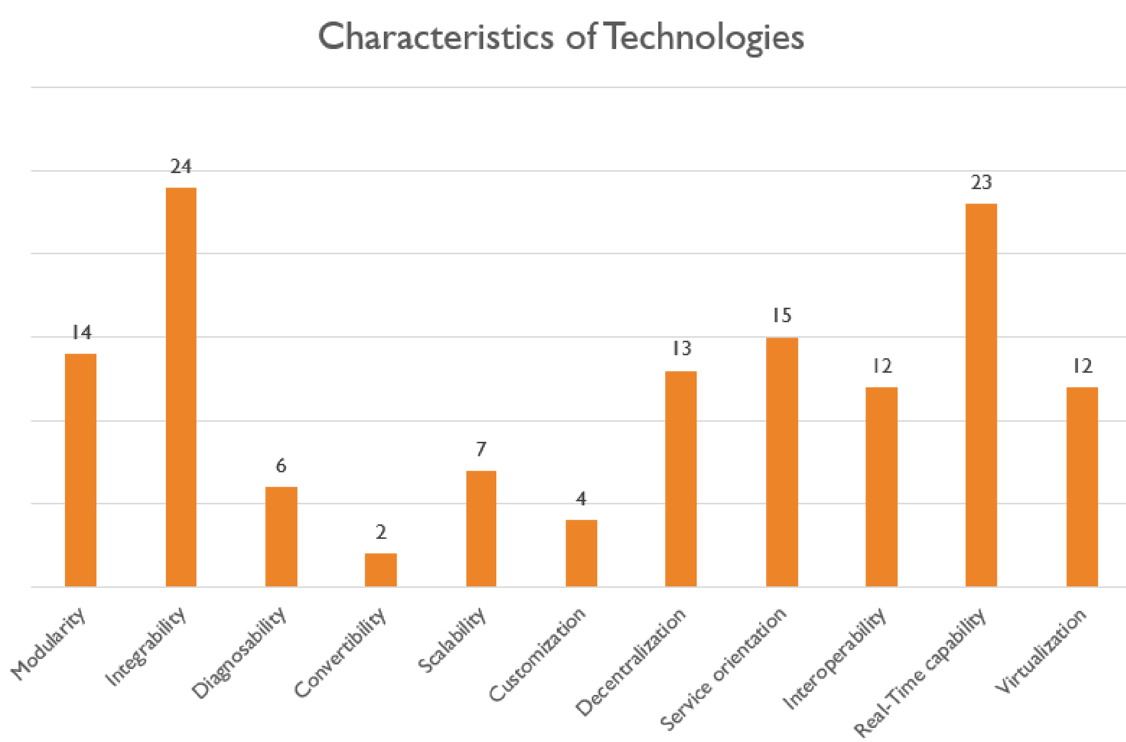

Figure 10. Characteristics of Technologies

Based on the definitions proposed by Alessia Napoleone (2018 and 2020) and other authors the table below (*Table 6*) lists the characteristics with their definitions respectively

Modularity	All system components, both software & hardware, are designed to be modular.
Integrability	Systems & components are designed for both ready integration & future introduction of new technology.
Diagnosability	Quick identification of the sources of quality and reliability problems.
Convertibility	Allows quick changeover between existing products & quick system adaptability to future products.
Scalability	Allows incremental changes of capacity, rapidly & economically.
Customization	Allows adaptation of system configuration for producing the required product families.
Decentralization	To work independently and autonomously in a way it remains aligned with a single goal.
Service orientation	Through interconnection & communication manufacturing tasks can be accomplished by several manufacturing services.

Interoperability	The capability of the system components to connect, communicate & operate with each other.
Real-time capability	Acquire & analyze real-time data on equipment, quality & raw materials & provide the derived insights immediately.
Virtualization	Link sensor data to virtual factory models and simulation models.

Table 6. Characteristics of Technologies definitions

A detailed representation was done again through a matrix (*Table 7*) to understand and to visualize in another way the relevance of each characteristic according to a spam time from 2007 to 2020. The table provides a visual representation of each technology on the X-axis and time on Y-axis. There is no real trend or pattern in time on the relevance of the characteristics, most of the authors present in each article at least two characteristics and some characteristics are more relevant than others.

Year	Papers	Modularity	Integrability	Diagnosability	Convertibility	Scalability	Customization	Decentralization	Service Orientation	Interoperability	Real-Time Capability	Virtualization
2020	A review on the characteristics of cyber-physical systems for the future smart factories	X	X	X	X	X		X		X	X	X
2020	User-Friendly MES Interfaces Recommendations for an AI-Based Chatbot Assistance in Industry 4.0 Shop Floors					X			X		X	
2019	Review of Digital twin applications in manufacturing			X						X	X	X
2019	Digital Twins and Cyber-Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison			X						X	X	X
2019	Building a reference model for a Manufacturing Execution System (MES)									X		
2019	An Overview of Next-generation Manufacturing Execution Systems How important is MES for I4.0		X					X	X		X	
2019	Multi-agent Manufacturing Execution System (MES) Concept, Architecture & ML Algorithm for a Smart Factory Case										X	
2019	Integration-and-testing-of-the-RFIDenabled-Smart-Factory-concept-within-the-Learning-Factory2019Procedia-ManufacturingOpen-Access										X	
2018	A framework to manage reconfigurability in manufacturing.	X	X	X	X	X	X					

2018	RFID Based Manufacturing Process of Cloud MES		X								X	X
2018	The impact of digitalization on the future of control and operations								X			
2018	The role of Digital Information Models for Horizontal & Vertical Interaction in Intelligent Production		X						X			
2018	Smart CPS vertical integration overview and user story with a cubit		X								X	
2018	Status-and-future-of-manufacturing-execution-systems2018		X						X			X
2018	Data-map--Method-for-the-specification-of-data-flows-within-production2019Procedia-CIRP		X									
2018	Workflow-management-for-edge-driven-manufacturing-systems2018							X	X			
2018	Manufacturing execution systems: The next level of automated control or shop-floor support?		X					X				
2018	A-Conceptual-Model-for-Developing-a-Smart-Process-Control-System2018Procedia-CIRP		X					X				
2017	Industry 4.0 _The evolution of Business Models							X			X	X
2017	The New MES. The backbone of Industry 4.0	X	X				X	X	X		X	X
2017	RAMI 4.0 based digitalization on an industrial extrude system.									X		

2017	Horizontal and vertical integration, as a requirement for cyber-physical systems in the context of Industry 4.0	X						X	X	X	X	X
2017	Exposing MES functionalities as an enabler for Cloud Manufacturing		X						X	X		
2017	PLM-MES integration to support Industry 4.0											X
2017	Digitalization of Manufacturing Execution Systems the core technology for realizing.	X	X				X	X				X
2016	Manufacturing Operation Management - The smart backbone of Industry 4.0	X	X					X		X	X	
2016	A Vertical and Cyber-Physical Integration of Cognitive Robots in Manufacturing											X
2016	The Industry 4.0 revolution and the future of Manufacturing Execution Systems (MES)	X						X		X		
2015	Manufacturing Execution System Present Situation and Development Trend Analysis	X	X			X						
2015	Research of Internet of Things applied to the manufacturing execution system.	X	X	X						X	X	
2015	A Proposal of Manufacturing Execution System Integration in Design for Additive Manufacturing		X	X			X				X	
2014	Ontology-Based Modeling of Manufacturing and Logistics Systems for a New MES Architecture	X	X			X			X			
2014	Modeling of RFID-Enabled Real-time Manufacturing Execution System in Mixed-Model Assembly Lines										X	

2014	mis: Virtualization aware manufacturing execution system	X	X			X			X		X	X
2013	Real-time data-driven monitoring and optimization method for IoT-based sensible production process.		X						X		X	
2012	Real-time data acquisition system and HMI for MES	X									X	
2012	An Approach for the Integration of a Scheduling System and a Multi-Agent Manufacturing Execution System. Towards a Collaborative Framework.							X				
2012	RFID-enabled real-time manufacturing execution system for mass-customization production										X	
2011	The evolution of Factory and Building Automation	X	X									
2011	RFID-enabled Real-time Manufacturing Execution System for Discrete Manufacturing: Software Design and Implementation										X	
2011	A radio frequency identification-enabled real-time manufacturing execution system for one-of-a-kind production manufacturing: a case study in mold industry										X	
2010	Distribution-of-MES-functionalities-for-flexible-automation2010							X				

2010	SOAbased-integration-for-batch-process-management-with-OPC-UA-and-ISA88952010		X						X			
2009	Manufacturing execution system a literature review	X	X			X			X	X	X	
2007	The continuing Evolution of Integration in Manufacturing Automation		X						X	X		

Table 7. Characteristics of Technologies according to literature

In the second part of this section, an analysis was carried out to understand how the authors present all these characteristics applied to MES. What is the relationship between MES and these characteristics? To illustrate this, a pie chart was created (*Figure 11*).

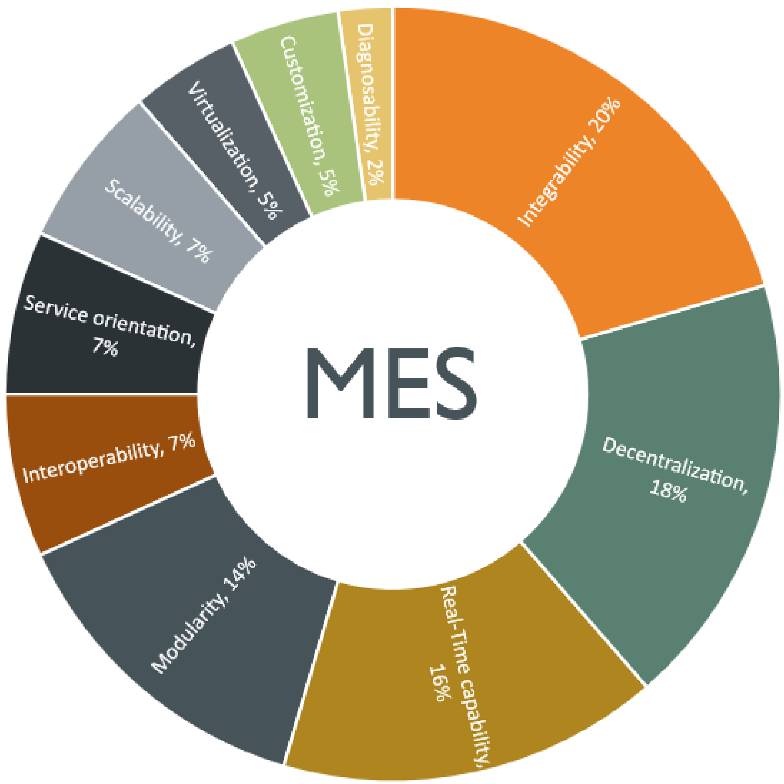

Figure 11. Characteristics of MES according to literature

It is noticeable that there are characteristics that are stronger in MES than others, the more representative ones and the must-have are *Decentralization*, *Integrability*, *Modularity*, and *Real-time capability*, which is associated with the matrix made in Section IV where the focus in the literature review was to improve MES in *Decentralization* and *Real-time capability.* As MES is a computerized system that controls multiple elements of the production process (orders, machines, services, flows, etc.) is logical that *Integrability* is the characteristic that most represents MES as its function is to integrate all the technologies and elements structurally and efficiently. Going further, a subgroup conformed of *Interoperability*, *Service orientation* and *Scalability* show a less strong but representative relation with MES. These characteristics should be on MES to be a more effective and functional system. And finally, *Virtualization*, *Customization,* and *Diagnosability* came as the less relevant in the literature.

The third analysis in this section is followed by creating a clustering model (*Figure 12*) between the technologies presented in Section IV and the characteristics presented in this section. The methodology used was to highlight in a visual way how these two topics are connected, the size of the inner circles represents the percentage of the technology that is related to each characteristic. Relevant information can be concluded from this model. Firstly, *Real-time capability*, a characteristic that is present in five of the technologies, proves the importance of having reliable and fast information, a move that currently MES must have to overcome the new challenges in the industry. Then is followed by *Interoperability*, *Virtualization*, *Service orientation*, *Diagnosability,* and *Integrability* as these technologies are represented by two-three technologies. And finally, with one technology associated, *Modularity*, *Decentralization*, *Customization*, and *Scalability*.

From the point of view of technology, is important to mention that CPS is present in all the characteristics giving a strong affirmation that is a complete technology with a high capacity to enable recent changes in the paradigm of Industry 4.0.

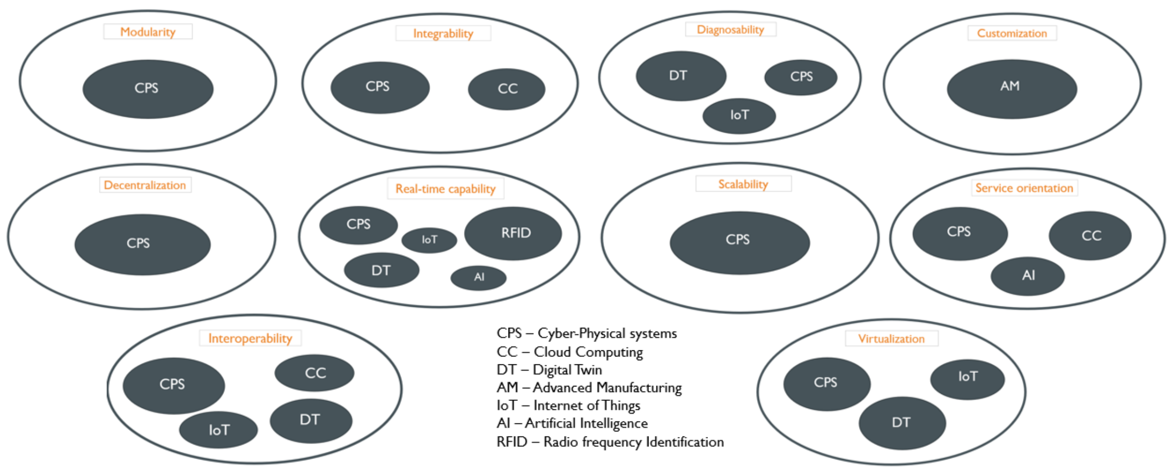

Figure 12. I4.0 Technologies and Characteristics Clustering

The last part of the analysis, to do a more robust analysis, is conducted by dividing what is the so call high-order characteristics and low-order characteristics and to understand the relationship between each characteristic.

High-order characteristics are more comprehensive characteristics proposed on this framework that can be associated with multiple low-order characteristics. They are graphically represented in *Figure13*.

- In the case of complementary: low-order characteristics are presented in juxtaposed circles.
- In the case of hierarchical relationship: low-order characteristics are represented in contained circles enabling other low-order characteristics or high-order characteristics.

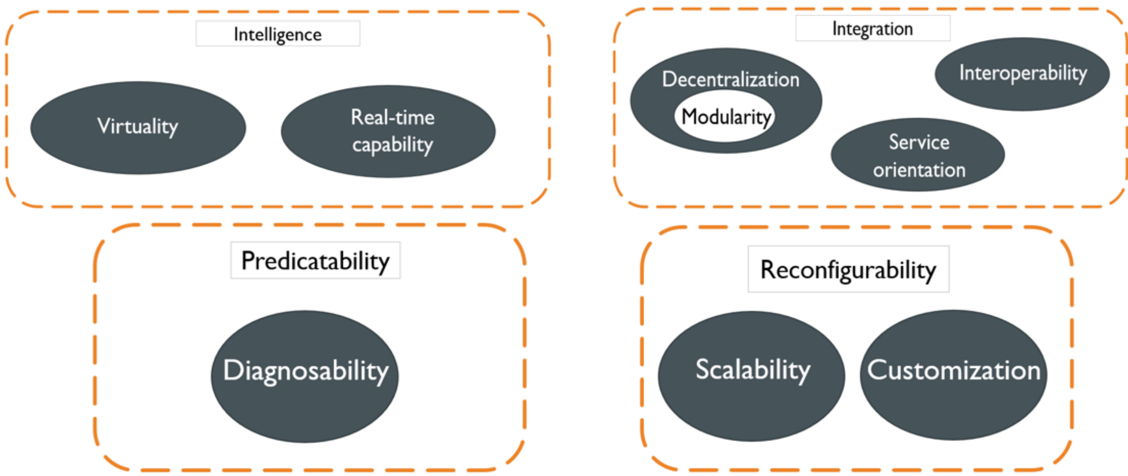

Figure 13. Comprehensive Schema of Technology Characteristics

Virtuality and *Real-time capability* have been cluster in the Intelligence high-order characteristic in the sense that these technologies are ruled by a smart capability to solve problems. Due to the characteristics of *Integrability*, this low-order characteristic was defined as a high-order characteristic renamed as Integration where it clusters the following low-order characteristics: *Interoperability*, *Decentralization*, *Modularity*, and *Service orientation*. *Interoperability* allows the development of communication and connectivity enabling integration among different elements. *Service orientation* integrates by its architecture approach aiming to develop a modular and independent application of services to provide a specific task integrating each module in concordance to the need. In the case of *Modularity* and *Decentralization*, there is a sub-hierarchical relation as *Decentralization* is composed of modules, which are characterized to be flexible, to work independently, and to make decisions autonomously leveraging an integration among different subsystems or modules.

Going further, *Diagnosability* enables *Predictability* to be capable to react to changes in the environment. *Reconfigurability* is the last high-order characteristic listed where *Scalability* complements with *Customization* to enable *Reconfigurability*. *Scalability* is the ability to change production quickly and *Customization* to configure production according to the needs of the customer they enhance Reconfigurability as an ability of MES to adapt to new challenges in terms of productivity. Is important to mention that Predictability and Reconfigurability are seen more as operational characteristic while Intelligence and Integration are taken from a technological perspective.

VI. Technologies and MES

This section, as stated before, will go deeper into each technology found in Section IV supported in some cases by some industrial successful stories, and explain through the most representative characteristic in each technology discussed in Section V how they impact MES.

i. Internet of Things

IoT is one of the most emblematic and representative technologies of I4.0. As stated in Section IV, this new technology starts to gain relevance since 2015 where more research was done to explore the potential of this technology. IoT refers to any device that can be connected to the Internet (IoT device) in real-time allowing two-way communication across or between shopfloors (Isaksson, A. J., Harjunkoski, I. & Sand, G., 2018). IoT also is a potential enable for Cyber-physical systems as it is a device capable to connect enabling an intelligent system. IoT devices are the "raw data generator" for advanced analytics and MES dashboards to deliver insights and useful information by helping MES in tracking and tracing to enforce and improve the production process at any stage. The type of data generated by IoT can be quite diverse ranging from quality data, the status of machines, faults, causes, and maintenance, among others. IoT devices need both data collection but also contextual information to make these data useful and take advantage of this technology. IoT is a technology characterize by *Real-time capability* and *Interoperability* framed in Section V, which helps MES in decision making and operational improvement as it is capable to connect and communicate in real-time a new type of information from the production line.

ii. Cyber-Physical Systems

This technology is the most important one that is having an enormous impact on MES as seen in previous sections, is characterized by six of the characteristics proposed in Section V. Is a complete technology that embedded other technologies (e.g., IoT, RFID, Digital Twin) and since 2015 has been a target of huge research on the industry because of its potential approach. CPS is a multidimensional and complete system that integrates the cyber world and the dynamic physical world. Through the integration and collaboration of computing, communication, and control, providing real-time sensing, information feedback, dynamic control, and other services (Tao *et al.*, 2019). In other words, CPS is a smart machine/device that complements the hardware (real world) and software (virtual world) to do a particular task. About this last point, some authors refer to the Digital Twin as the digital counterpart of the CPS that is embedded in it, becoming a potential tool to diagnose or prevent future behavior on a particular object. It can identify itself and know its state and position on the production line, it contains sensors, actuators that enable the system to work correctly, it is capable to analyze data and have its autonomous system making its own decisions. And one of the most notable features is the ability to connect to other CPSs, creating what is so-called Cyber-physical production systems (CPPS), consisting of autonomous and cooperative elements and subsystems that can connect across all levels of production.

Is *modular* as the components are designed in that way. Is *decentralize* because each module is capable to work independently and autonomously. These two characteristics impact MES in the production flow as no more centralized flow is required generating a more autonomous flow according to the product specification. Is *interoperable* and has *integration* among the modules as is capable to connect, communicate, operate and is ready to integrate all the elements. A characteristic that currently is vital in MES, with a CPS technology these elements must keep embedded in the core of MES, as more independent elements are created, a more robust integration MES should have. Has *Virtualization* as is characterized by sensors enabling simulation models of the real world. This impact particularly on MES as new, more detailed, and accurate information provided, is causing a restructuring on how MES currently received information. And has a *Real-time capability* because it embedded IoT and RFID devices that are capable to provide information in the exact moment making MES more reliable and accurate.

iii. Cloud Computing

Cloud Computing with no exception is another revolutionary technology that is reshaping the way business models are made in a scalable and service-oriented way. Because of this, is now an element in the I4.0 reaching a higher concern of interest and where enterprises are investing. Based on the definition of Christos Alexakos and Athanasios Kalogeras (2017), Cloud Computing is an emerging model providing access to computational resources as utilities to end-users according to their demands. Its growth is due to centralized storage, memory, processing, and bandwidth that lead to a more efficient cost model. Cloud Computing impact on MES through *Integrability* and *Service orientation* as listed in Section V. MES is capable to integrate different services provided by the Cloud (e.g., the interaction between public and private Cloud) and enhance in the horizontal integration with other enterprises, as more information has been shared among the supply chain to optimize the scheduling of resources accordingly. As Cloud computing is based on services, *Service orientation* is the core of this technology. To better illustrate this a visual representation (*Figure 14*) is presented (Moraiu *et al.*, 2015) showing a service-oriented manufacturing system to cloud.

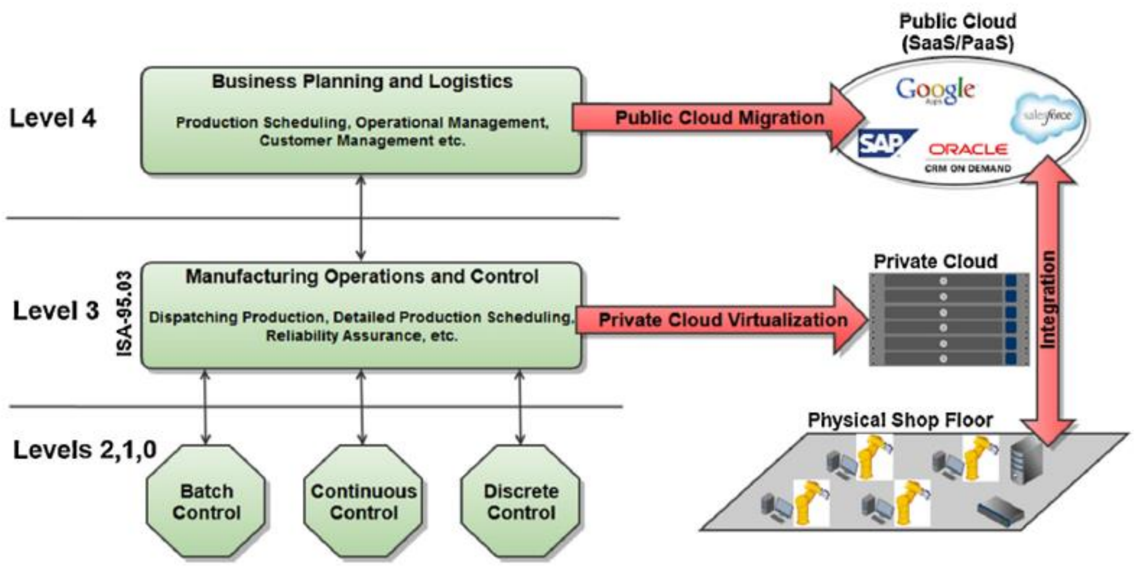

Figure 14. Cloud Computing framework (Moraiu)

Where you have local and public at a different level of production. There are service providers (e.g., Google, SAP) that are able for example to provide to a company an algorithm already trained to manipulate data, they sell this service to save time and effort for the company, or they provide storage coverage by seasonality according to the companies' needs. These characteristics of Cloud Computing have a positive effect on MES, leveraging the performance in different perspectives some of them support better preventive maintenance, improve customization, and optimization on the processes, also the ability through services to export selected views from MES out to big data structures allowing the production context to be fully captured and the new data analytics created by Cloud Computing must update MES model to enhance throughput, yield and uptime (e.g. Machine Learning).

iv. Artificial Intelligence

Artificial Intelligence is a system's ability to interpret external data correctly, to learn from such data, and to use those learnings to achieve specific goals and tasks through flexible adaptation (Haenlein and Kaplan, 2019). Now a day is one of the most invested technology and a key one to convey with the paradigm of I4.0. This technology covers a wide range of applications and industrial sectors. Particularly in this work is taken as literature support to understand the potential advantages of using Artificial Intelligence a success story implementation documented by Mantravadi and Aalborg University (2020) using *chatbot* (a collaborative robot that interacts with humans using Artificial Intelligence) to support manufacturing operators. The implementation was carried out to compare a traditional MES user interface and MES with a chatbot user interface to retrieve order information. *Figure 15* shows the outcome. Firstly, the relationship and logic of the system, showing how they obtain the information and how is trained using a machine learning algorithm, in this case, a neuronal network, and secondly the user interface where the operator ask the chatbot the information and in real-time, the chatbot retrieves and provides the information needed without the operator having to search for the information in the database. This implementation shows the potential advantage that this technology can provide to MES. Through *Real-time capability* this technology can help personnel to make more informed decisions in a faster way making MES a more accurate informative system, this has enormous potential as more data are created with I4.0, an AI system particularly a chatbot, is capable to be more accurate, because of the learning from raw data and experience. It is of great support also to novice operators that do not are well-familiar with the process, as it provides in-hand without minimal effort useful information. This could be a potential substitution to navigation through complex or unintuitive interfaces in MES or even complement it with MES dashboards to achieve a more efficient way to obtain information through the system.

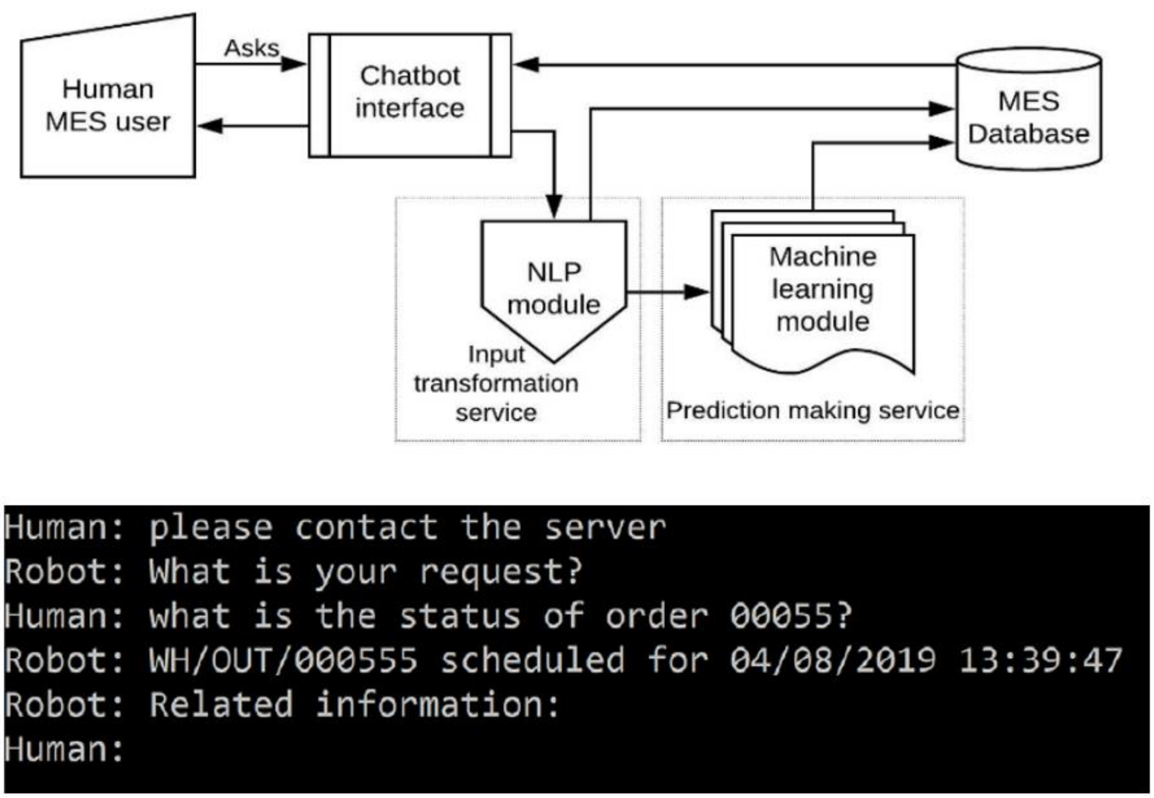

Figure 15. Aalborg University Chatbot implementation

v. Digital Twin

Digital Twin is a type of simulation that due to new technological improvements is becoming a reality as it provides high advantages and effective solutions to the industry. A Digital Twin creates high-fidelity virtual models of physical objects in virtual space to simulate their behaviors in the real world and provide feedback. It enables companies to predict and detect physical issues sooner and more accurately, optimize manufacturing processes and produce better products (Tao *et al.*, 2019). A model representation is given by the author (*Figure 16*) to illustrate how the physical and virtual worlds are connected. The left side shows how through sensors (even other technologies like RFID or IoT) the bridge of communication is done with the virtual world that is represented on the right side, showing the virtual representation of the object where process models are done, the data that are generated on the virtual world is sent back to the physical world updating any parameter. Digital Twin technology can improve MES through *Real-time capability* as data obtained by the virtual world is available In the same moment, *Interoperability* as the Digital Twin is capable to connect different devices (e.g. sensors) to simulate the real world, though *Virtualization* as this technology is capable of virtualizing a physical object and by *Diagnosability* because of the simulation model its capable to simulate scenarios and behaviors of machines/object that can lead to preventing possible failures or downtimes. This technology also enhances the availability of the data in the field obtain by the virtual models, increases the reliability of equipment and production lines.

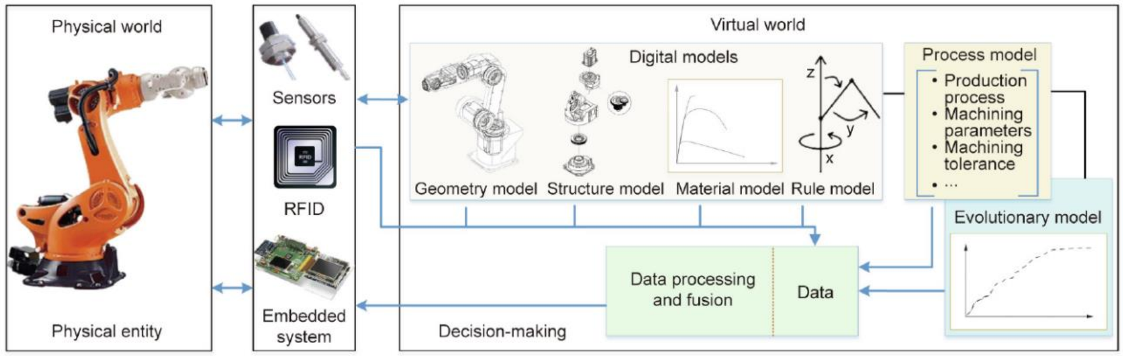

Figure 16. Digital Twin framework (Tao)

vi. Radio Frequency Identification

RFID is particularly a low-cost and old technology that has existed for decades. This is supported by the matrix presented in Section IV showing that this technology is present in the literature review before the rest of the technologies. RFID devices are used to track manufacturing objects, through reading and writing radio signals, without physical or optical contact with the objects to be identified (Yang, Z. *et al.*, 2015). This technology has been used in different industries for identification and tracking purposes, usually is made of silicon tags that inherit have a radio transponder that is triggered by electromagnetic pulses transmitting digital data. Nowadays, with the I4.0, this technology has gained attention as a potential tool to obtain more reliable and real-time information about products/machines that hold their positioning coordinates in the manufacturing industry. The *Real-time capability* provides an improvement on MES tracking and precision information about status, position, and activities done in the production line. The author Wang (2018) provides a framework illustrated in (*Figure 17*) to understand better how RFID tags work and interact with other technologies (e.g., IoT, Cloud Computing) on different layers of the manufacturing process.

It can be visualized that RFID is in the bottom layer directly on the product. The technology enables the real-time tracking and position of the machine/product that is sent through an IoT layer to the MES. This is an interesting configuration as this technology is making normal products to be smart, as they are the ones that carry their information (e.g., production order, quantity, status, position) and providing directly to MES making it more effective and useful informatic system.

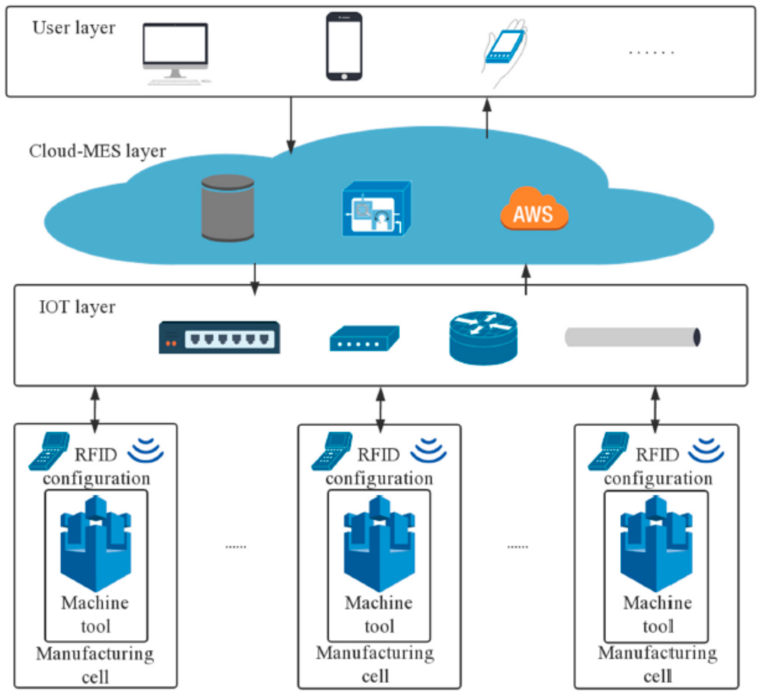

Figure 17. RFID framework (Wang)

A company success story presented by Zhong (2013) shows the implementation of the RFID tag on an Indonesian company's shop floor (*Figure 18*) providing the logic and location of each tag in the operator, machine, and product. Is to highlight that its easiness of implementation, the low investment, and the useful information that can be obtained from it, make it an interesting technology to be implemented in MES in the I4.0 era.

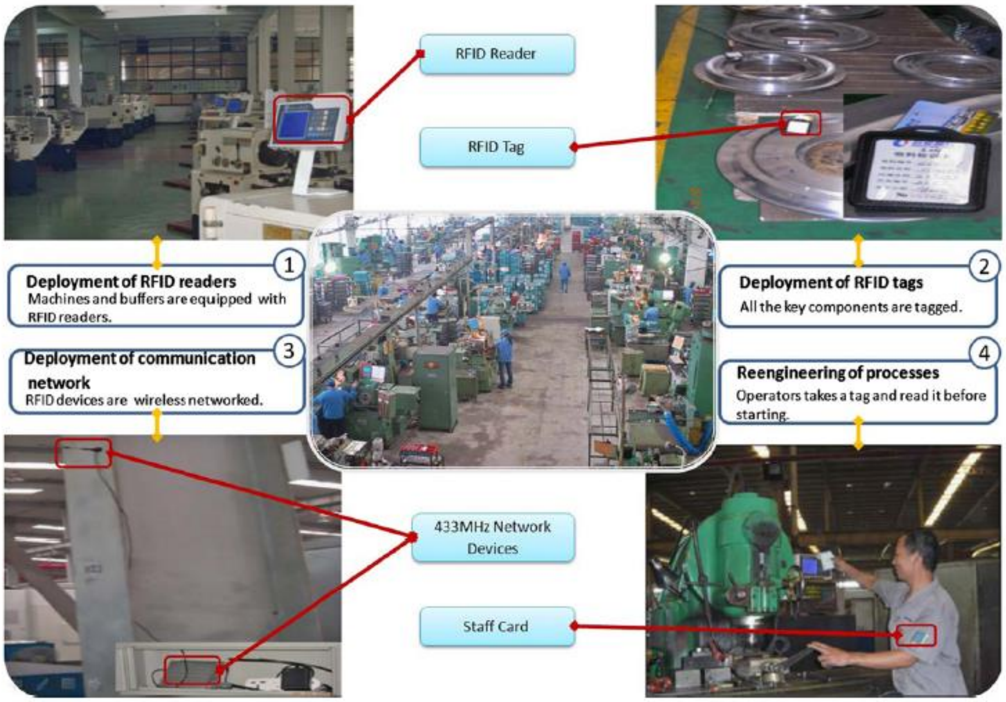

Figure 18. RFID implementation (Zhong)

vii. Additive Manufacturing

Additive Manufacturing is one of the newest technologies that is taking a big interest in the field. It is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining (D'Antonio *et al.*, 2015). Talking particularly about the relationship with MES, this technology is not improving MES like the rest of the technology presented in this paper. But it is taken into consideration as is a technology that is becoming a trend and MES needs to be adapted to the new requirements of this type of manufacturing as new post and pre-processing operations are needed. *Customization* is the characteristic Additive Manufacturing can provide as it is capable to create more complex products and able to fulfill more efficiently the requirements of the client. D' Antonio presents a model (*Figure 19*) to emphasize how MES and this technology can be correlated to improve product quality and process performance. Though a design software (DFAM), the cad file is created and printed accordingly to the design, MES task is to analyze the physical piece through sensors and collet in real-time the information about the product to send the feedback to the DFAM to modify the design if it is out of compliance, this way the quality of the product is in control and it is assumed that the piece leaves the shop floor fulfilling the requirements.

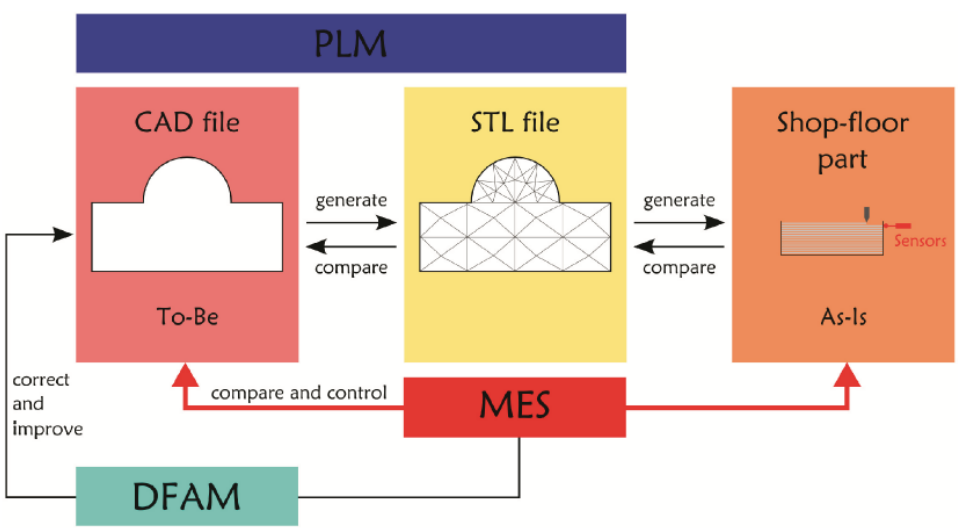

Figure 19. Additive Manufacturing framework (D'Antonio)

VII. Traditional MES and New generation MES

In this section, a brief explanation about the traditional and new MES is presented to understand the main difference and how the new technologies are reshaping the way MES is executed in different premises.

i. Traditional MES

Traditional MES is considered as the bridge between the shopfloor and the business level, this is supported because of a well-hierarchical automation pyramid where each layer has its development and MES is well defined in the third level. MES is centralized and defines with fixed axes. Another characteristic is the strong integration to the ERP and the ownership of the automation control of the lower levels (e.g., SCADAs, PLCs) providing some intelligence on the floor shop. This traditional MES has not to be designed to aggregate data in real-time or store data efficiently for long periods.

ii. New generation MES

The new generation of MES is perceived differently from being just an informative system to the upper/business level, a simple process execution tool, to an integrative application system, be capable to deal with complex manufacturing flows. The new generation of MES task is to digitize the shop floor for data collection, analysis, and exchange of real-time information by giving an "all-around view" of resources. Must be modular, service-oriented, and digitized. Ready to process IoT and RFID data, virtualized processes with Digital Twins, manufacture with Additive Manufacturing, provide information, diagnostic with the help of

Artificial Intelligent, and capable to store, analyze big data and to provide cloud services. Able to connect different CPS through a distributed manufacturing control to sustain a marketplace on the production floor breaking the traditional centralized flows.

According to Fraser (2017), *Figure 20* illustrates how the new generation of MES can be more flexible and dynamic on the production flow, he compares the current approach to the I4.0 approach, it is important to understand the importance of modular station connected between them. *Figure 21* illustrates the main function of the new MES from a multi-agent perspective, where it acts as the broker in a marketplace of different CPS connected between them. The customer order is released and then each CPS is capable to tell if they are available or not to produce it, in this way MES assigned the task to an asset that provides the most feasible solution in terms of cost and time.

It is to highlight the importance of CPPs for MES as is the backbone of execution on MES in the production flow, complementing and interacting among them and with other technologies presented on this paper like IoT, Cloud Computing, Digital Twin, among others.

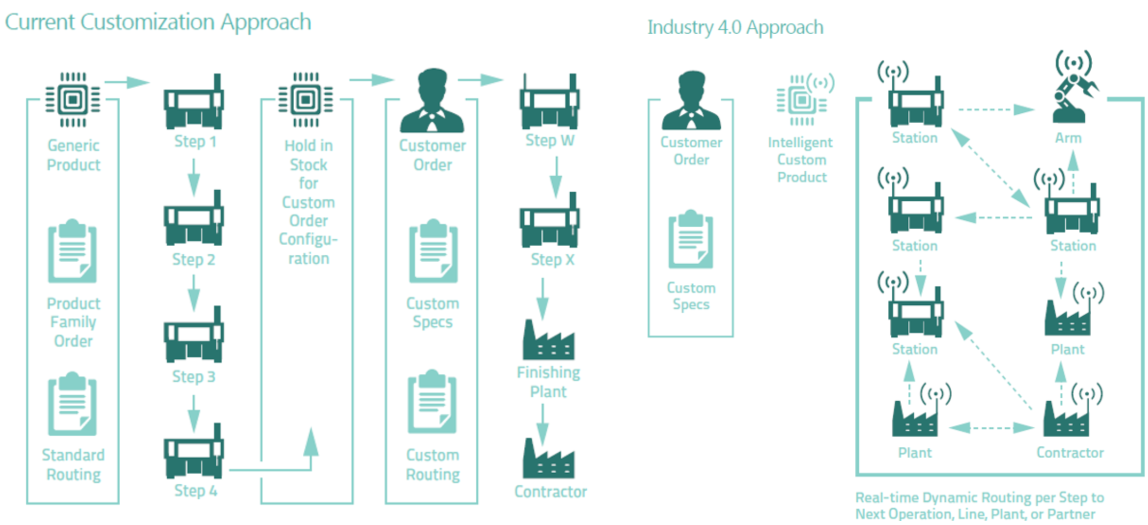

Figure 20. Current & I4.0 customization approach (Fraser)

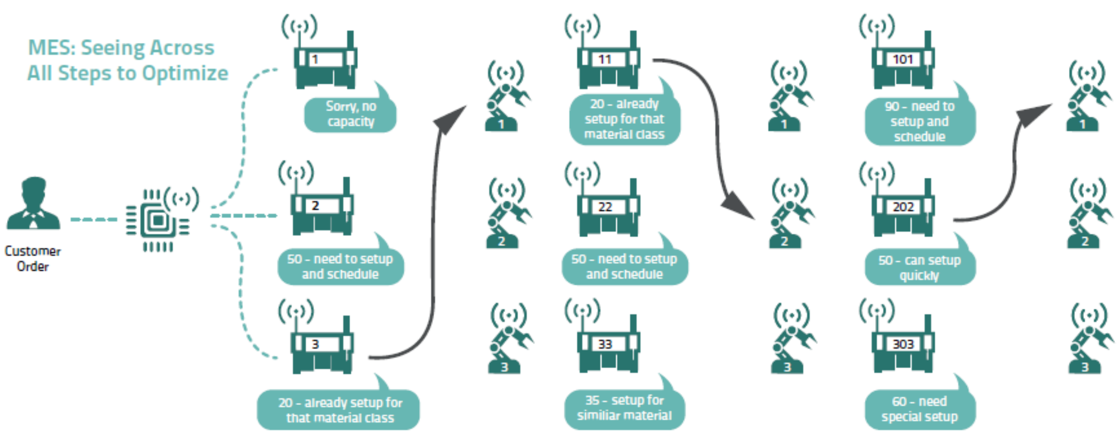

Figure 21. New MES logic flow (Fraser)

VIII. Discussion

There are several findings to discuss the framework presented in the previous chapters. Starting from MES as an informatic system. The main objective and concept of it have changed, is no more a bridge of information and just a system that can compile information according to what the organization needs. With Industry 4.0 here, MES is changing radically, and it is happening through the technologies presented above and other emerging technologies. To point out that CPS is the most complete of the technologies presented because it includes simultaneously different key characteristics that are revolutionizing MES in all aspects, from this the well-deserved name "backbone of the new MES". As for MES to cope with the requirements of Industry 4.0 a CPS embedded in the system is essential. This led us to another important finding to comment on, some technologies are having a stronger impact in MES than others, as some characteristics presented in the framework are more relevant and important than technologies need to have. The new generation of MES is changing in the way it executes distinct functions and the way it interacts with other systems. Looking at a new generation, MES is working and providing information differently in an era where data are fundamental for the business to run. The technologies of I4.0 are and will generate a huge amount of data that new MES is now capable of and should be able to obtain most efficiently and effectively. A big finding is to understand that today MES must be decentralized in a multi-agent perspective and be able to obtain data in real-time.

There are some implications that this work can provide to the Industry. It helps practitioners in the industry to identify key elements and have an overview of the potential of Industry 4.0 applied to MES. An overview of the most important technologies of the I4.0 on how exactly they are impacting MES. Knowing the "how" is a strategic approach to know from where to start. Knowing "how" each technology and what characteristic each technology has, help potentially in the easiness of the implementation. Practitioners now are capable to see which technologies could be easier or harder to implement and what elements should they expect to have to implement them.

IX. Conclusion

The work proposed a framework to understand how the technologies that have emerged on Industry 4.0 are impacting the new generation of MES. Through a systematic literature review the objective research question: *How these new enabling technologies in Industry 4.0 (such as RFID, Cloud Computing, IoT, Additive Manufacturing, etc.…) are changing the MES to support the manufacturing industry?* has been answered by reaching firstly, *What are the enabling technologies of Industry 4.0?* the most relevant technologies in Industry 4.0, then by answering *What are the characteristics of these technologies?* an analysis of how they impact the industry by executing another systematic literature review on the main characteristics a technology should contain. And finally, with the information collected, how MES is modified by these technologies through their characteristics. The following table (*Table 8*) summarizes the findings:

Technology	Characteristics	Impact
Internet of Things	Interoperability	IoT devices are capable to connect and communicate providing useful information to MES.
	Real-time capability	Fast and reliable information is obtained by the IoT devices to feed the information system of MES.

Cyber-Physical Systems	Modularity	CPS being modular helps MES to develop a decentralized structure.
	Decentralization	It enables MES to have a marketplace flow taking the advantages of a distributed platform.
	Interoperability	CPS can connect and communicate providing useful information to MES.
	Virtualization	Virtualizing the physical part of the CPS help MES to obtain information by simulating different scenarios.
	Real-time capability	Fast and reliable information was obtained by the CPS to feed the information system of MES.
	Integrability	By integrating different components on an overall system makes the CPS more robust and effective for MES.

Cloud Computing	Integrability	By being capable to integrate different services it makes the Cloud more robust and effective for MES.
	Service orientation	Service-oriented cloud supports MES to be more flexible and generate a modular platform taking the advantages of this architecture.
Artificial Intelligence (Chatbots)	Real-time capability	Fast and reliable information generated by the chatbots feeding the information system of MES.
Digital Twin	Real-time capability	Fast and reliable information generated by the Digital Twin simulation to feed the information system of MES.
	Virtualization	Virtualizing the physical world helps MES to obtain information by simulating different scenarios.

	Interoperability	Digital Twin is capable to connect and communicate with sensors in the physical world to be more precise on the information provided to MES.
	Diagnosability	The ability to predict and identify future problems help MES to be a preventive system.
Radio Frequency Identification	Real-time capability	Fast and reliable information was obtained by the RFID tags to feed the information system of MES.
Additive Manufacturing	Customization	MES takes a great advantage as is capable to fulfill in a better way the customer requirements and need.

Table 8. Framework findings

With the results of this framework, there are several implications to be considered. The results show an interesting way to understand the relevance that MES is having in Industry 4.0, to understand the potential and capability it to cope with the new challenges. According to the needs, this framework can present different technologies that can adjust to any industry, to the requirements of the client and the potential they have combining it with MES. It is to mention that the implementation of this paradigm is not an easy task going, where a strong effort, investment, and commitment must be done as it modifies different internal structures within the company.

i. Limitations

There are some limitations to this work, although it presents a general overview and a way to understanding the impact of the technologies of Industry 4.0 on MES, only two search engines (Google Scholar and Scopus) were considered for the literature review and no other, limiting a more robust and comprehensive literature review with additional useful information from the field. Secondly, only success stories and theoretical frameworks were considered rather than also including the requirement of the industry. A third limitation was the explanation and impact of each technology as they were presented from a qualitative point of view taking out of the scope the impact and success stories from a quantitative way.

Additionally, this framework was limited only considering the planning level (MES) of the actual automation pyramid and not the rest of the automation pyramids like control, supervisory (e.g., PLC, SCADA), or the enterprise level (e.g., ERP), reducing the overall understanding on the implications of Industry 4.0 at all levels of the company and the relationship between them.

ii. Future works

The framework proposed should be considered as a starting point of further research works. An interesting topic could be how the structural changes on the company are impacted by these technologies, which exact implications or effort to be done and to differentiate how on each manufacturing industry (e.g., fashion, chemical, automotive, food) could differ, supported by more extensive success stories within companies. This could also be supported by measuring these efforts with statistical tools and finding relevant correlations within the changes and the technologies.

Additionally, another research topic could be associated with the business level side. Taking this framework as a base, and knowing the impact from a technical point of view of each technology a probable future research topic could be presented as *How these new enabling technologies in Industry 4.0 (such as RFID, Cloud Computing, IoT, Additive Manufacturing, etc.…) are changing the planning and enterprise automation pyramid level from a business and economic perspective?*

This is an interesting topic as there is not yet enough knowledge on the relation between Industry 4.0 and economical implication of it. Strong research has been done from the technical point of view, finding robust information on the potential of this new paradigm and the technologies within it. As this is a revolutionary era the manufacturing industry is facing, it is strongly important to understand the new challenges companies are facing from the economical perspective and the potential advantages of Industry 4.0.

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