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Investigating the impact of Industry 4.0 technologies on ETO supply chains

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Alla mia famiglia, agli amici

Sommario

ABSTRACT

To maintain the competitive advantage and to survive in a world that is becoming more and more uncertain due to economic, cultural and political factors, firms are nowadays embracing the principles and knowledge forwarded by Industry 4.0. In particular, companies adopting an Engineer to Order (ETO) fulfilment strategy are among the contexts that are mostly experiencing such transformation, although literature is not widespread referring to this topic. For this reason, an initial overview of the most important paradigms used in ETO industries will be provided, to better understand at a later stage the influences of the new technologies. Then, the analysis will be branched into three main roots, according to the three typically ETO sectors taken into consideration: Aerospace, Machinery and Shipbuilding.

The final purpose of the thesis consists in providing a portray of the actual situation of Engineer to order supply chains (SC) in relation to Industry 4.0 (I4.0) technologies, identifying the most prominent ones and the strongest barriers that inhibit their implementation. In the end, a crossover analysis will be presented with the aim of catching similarities and differences between the three industries, looking at the possible way of I4.0 implementation.

ESTRATTO

Per mantenere il vantaggio competitivo e sopravvivere in un mondo che sta diventando sempre più incerto a causa di fattori economici, culturali e politici, le aziende oggi stanno abbracciando i principi e le conoscenze trasmesse dall'Industria 4.0. In particolare, le aziende che adottano una struttura di tipo Engineer to Order (ETO) sono tra i contesti che stanno maggiormente vivendo tale trasformazione, sebbene la letteratura non sia molto diffusa su questo argomento. Per questo motivo, verrà fornita una prima panoramica dei più importanti paradigmi utilizzati nelle industrie ETO, per meglio comprendere in una fase successiva gli influssi delle nuove tecnologie. Quindi, l'analisi si svilupperà seguendo tre filoni principali e prendendo in considerazione i settori che sono tipicamente classificati come ETO: Aerospaziale, Macchinari e Costruzioni navali.

Lo scopo finale della tesi consiste nel fornire un quadro della situazione attuale delle supply chains di tipo Engeneer to order in relazione alle tecnologie dell'Industria 4.0 (I4.0), individuando quelle più evidenti e le barriere più forti che ne inibiscono l'implementazione. Alla fine, verrà presentata un'analisi crossover con l'obiettivo di cogliere somiglianze e differenze tra i tre settori, guardando alle possibili modalità di implementazione di I4.0.

OBIETTIVO DI RICERCA

So far, very poor literature experimented the linkage between Engineer to order (ETO) and Industry 4.0 (I4.0), and more in general ETO has always been put behind respect to other most developed typical order fulfilment strategies. Now, ETO supply chains (SC) are emerging and gaining an increasing importance as more customized products are demanded, independently from the type of industry.

Therefore, this research serves as an investigation regarding the main technologies introduced with the coming of Industry 4.0, focusing in particular on its ability to support supply chain management tasks. About that, one of the most famous models, LARG paradigm (lean, agile, resilient, green) will be introduced to understand which strategy is more suitable to solve the issues of very particular supply chains like ETO's one. In addition, the research will take into consideration the scientific characteristics of the different technologies to identify the most suitable fields of application, matching with the characteristics of the industry in which they are applied.

The research will not focus on the implementation from a strictly technological point of view, rather from an organizational one, that is trying to study the coordination between all the new resources, actors, tools in order to deploy a new way to manage the whole supply chain.

Based on these objectives the following research questions are posed:

RQ1: what is the state of the art of I4.0 implementation in ETO supply chains and what are the main enablers and barriers that are influencing this process?

RQ2: what are the most promising I4.0 technologies? How they affect the organizational structure of ETO companies?

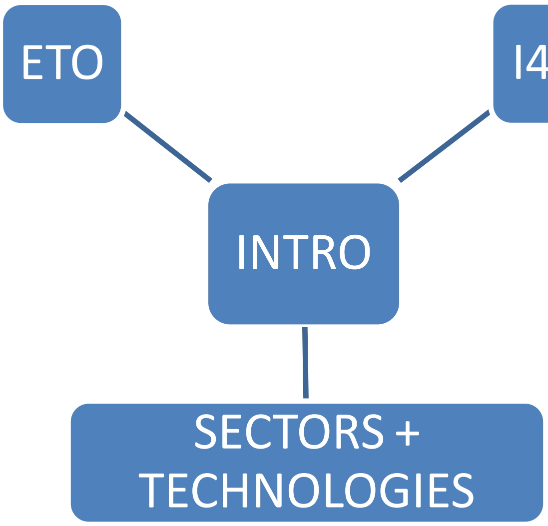
RQ3: what are the main issues that the ETO sector is facing and how the new technologies can help solving them?

INTRODUCTION

The structure of the introduction will reflect the two main topics that the thesis will attempt to investigate and combine:

1. The first part will be devoted to ETO supply chains.
2. The second part will be focused on I4.0 and its main technologies.

The purpose of such distinction is to better study the two phenomena, in order to get a comprehensive picture about their main characteristics. Finally, the objective of the thesis will be to rematch the two parts, trying to discover and bring out connecting points between the different ETO sectors and the new technologies of Industry 4.0.



Therefore, the output of this process will become the input of the thesis, providing:

- a series of sectors that are more suitable for the implementation of I4.0 technologies, since they face similar/comparable problems.
- a series of technologies that seem to be prompt for solving the most common issues across the various industries.

ETO

The analysis of Engineer to order supply chains will take inspiration from the paper of (Gosling and Naim, 2009), a literature review whose overall aim was to provide an exhaustive picture of the topic, coming up with an initial division of the ETO industries. Subsequently, it will be the starting point of this thesis.

First, it is important to understand why ETO is becoming so crucial in the latest years. The reason resides in the new megatrend that is universally affecting every kind of industry: the phenomenon of customization. Rivalry among companies is constantly increasing and the new source of competitive advantage shifted from the efficiency in production to the ability to build relations and interaction with customers, in order to better capture their feelings and needs.

- ➔ Therefore, the ETO model, with its high degree of customization (if compared to other structures), is gaining more and more importance. Such personalization is obtained encompassing the customer, at the beginning of the project (at the engineering and design phase).

Second, it is relevant to understand how the literature defines ETO. In regard, in order to describe all possible range of operations, six different supply chain structures are commonly identified:

1. engineer-to-order (ETO)
2. buy-to-order (BTO)
3. make-to-order (MTO)
4. assemble-to-order (ATO)
5. make-to- stock (MTS)
6. ship-to-stock (STS)

The structure is perfectly represented in Figure 1.

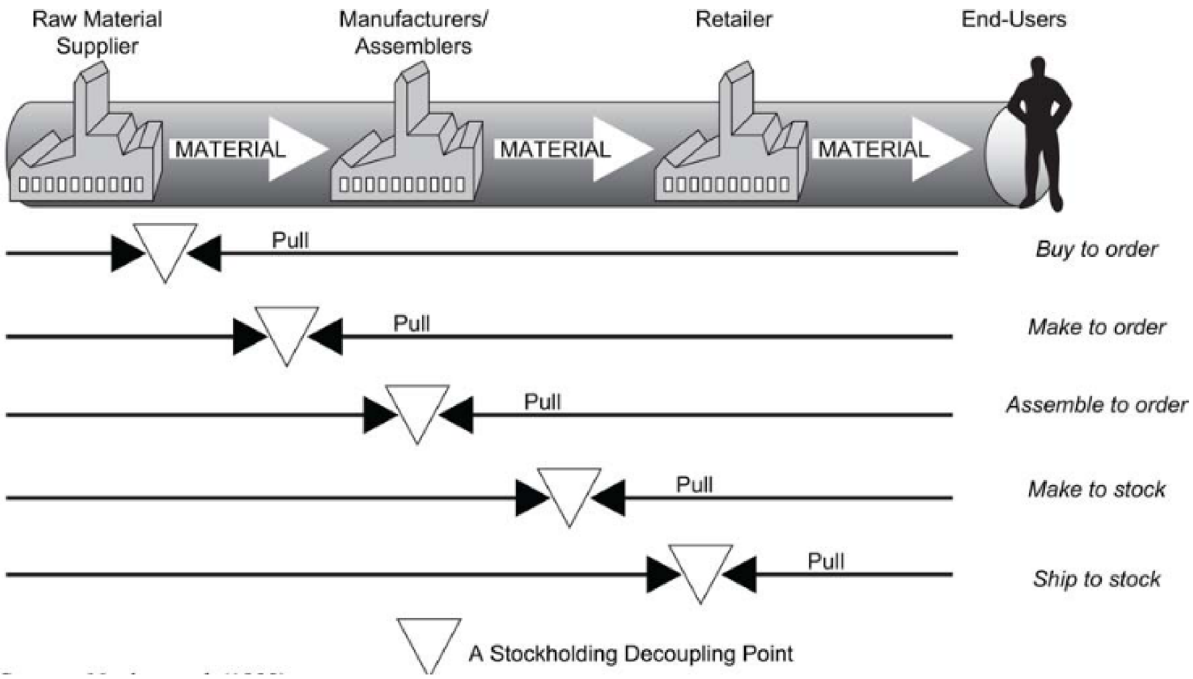


Figure 1. Different Supply Chain Strategies (Rahimnia and Moghadasian, 1999)

The discriminant element that makes all the supply chain structures intrinsically different from each other is the “decoupling point”. According to Gosling and Naim (2009), the customer order decoupling point (CODP) is a stock holding point that separates the part of the supply chain that responds directly to the customer, from the part of the supply chain that uses forecast planning. Going more into details, the decoupling point can act as a strategic buffer against the variability in demand, allowing a rapid reaction to unexpected hitches.

- Upstream (from the CODP) all products are produced to forecast;
- downstream (from the CODP) all products are pulled by the end-user (Rahimnia and Moghadasian, 1999).

In ETO supply chains the decoupling point is located at the design stage, where the customer directly influences the operations. Therefore, these supply chains are perfectly suitable for those sectors like construction or capital goods, where large and complex project must be managed with a direct intercession of the client.

Although it is one of the most peculiar supply chains, ETO shares some commonalities with other SC structures, also with one diametrically opposite like Make to Stock (MTS). Therefore, different authors tried to assess enhancing elements that ETO could gain from MTS.
They usually came to similar results. To make some examples:

- Ramirez-Peña *et al.* (2020) propose some initiatives connected to the concepts of just in time and supplier development process, directly taken from high-volume sectors:
    - reduction of the number of suppliers
    - development of deeper and longer lasting relationships
    - consider suppliers as part of in-house manufacturing

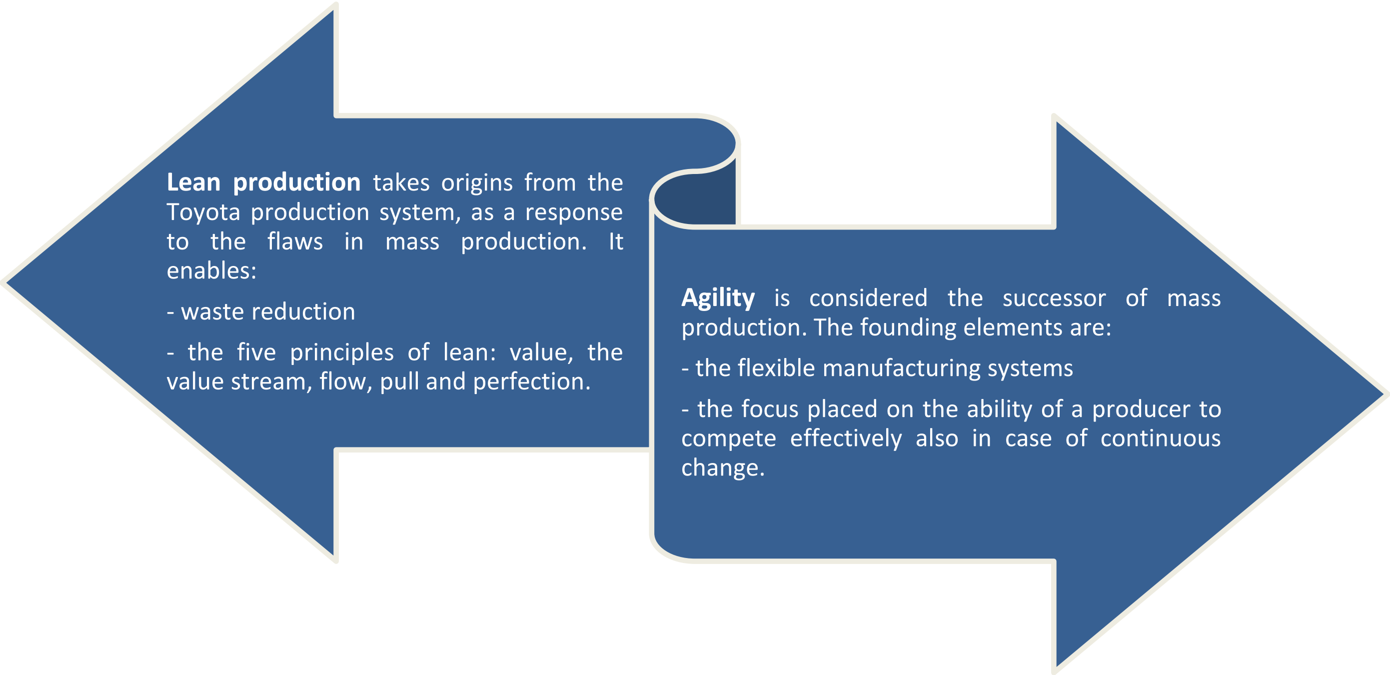
- Hicks, Mcgovern and Earl (2000)**,** in the same way, emphasize that some lessons can be learnt from high volume sectors, recalling similar initiatives like the previous study:
    - reduction of the supplier base
    - long terms relationships

Anyway, it is necessary to make one point clearer. The very characteristics of ETO market significantly constrain the application of established supply chain management methods (Gosling and Naim, 2009). About this:

- Briscoe (2005) found that it is not always possible to adopt strategies of supplier base reduction, as in the case of construction. The intrinsic features of this sector, like the large number of supply chain partners and the consequent level of fragmentation, place constraints to the level of supply chain integration that is possible to achieve.

Another relevant topic will be introduced: the study of the main paradigms of supply chain management practices. The two most famous archetypes are Lean and Agile. They are fundamental in order to discover additional features typical of ETO supply chains. Moreover, they can be used as a connection between different companies and industries, becoming a point of comparison.

To better understand this topic, Figure 2 is detected, getting inspired by the paper of Gosling and Naim (2009), in relation to lean thinking and agile manufacturing.



Lean production takes origins from the Toyota production system, as a response to the flaws in mass production. It enables:

- waste reduction
- the five principles of lean: value, the value stream, flow, pull and perfection.

Agility is considered the successor of mass production. The founding elements are:

- the flexible manufacturing systems
- the focus placed on the ability of a producer to compete effectively also in case of continuous change.

Figure 2. Lean and Agile definition (Gosling and Naim, 2009).

What emerges from literature is that there is disagreement about applicability and boundaries of the two paradigms, making it difficult to identify and distinguish their definitions and philosophies, (Christopher and Towill, 2001). Few examples:

- Soltan and Mostafa (2014) stated that lean is a prerequisite for agile supply
- Papadopoulou and Özbayrak (2005) argued that lean is an umbrella and agility is just a part of it

Summarizing, a possible distinction was provided by Ben Naylor, Naim and Berry (1999), who tried to make clearer the difference between lean and agile, putting lean in relation to the concept of waste elimination, both in terms of resources and time, and agile to the ability to use market knowledge to exploit profitable opportunities in a volatile marketplace.

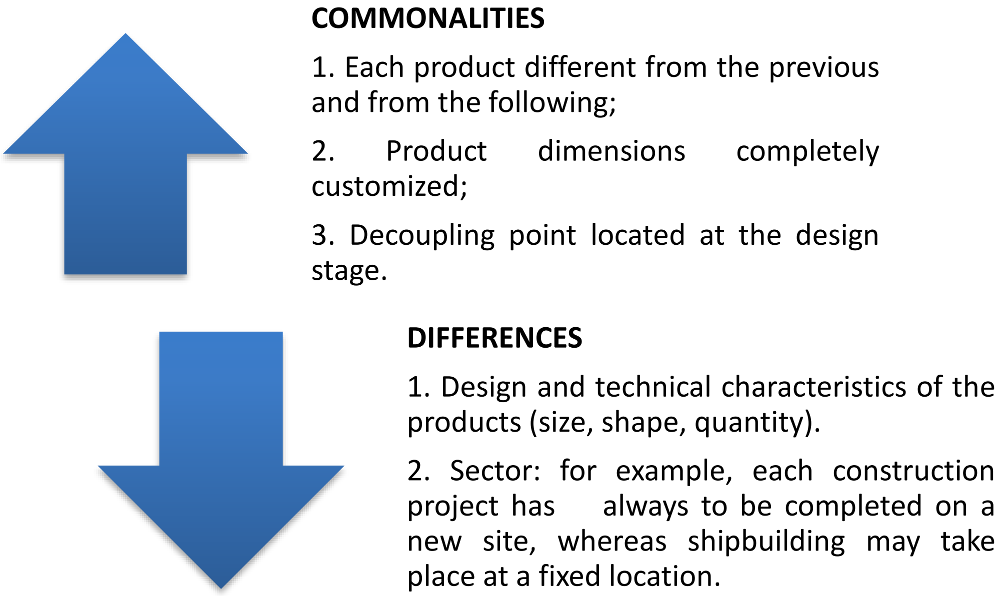
Properly starting from these considerations, the research will try to better divide lean and agile, addressing in a more detailed way which of these paradigms can be more suitable to be implemented in ETO supply chains.

About this, the starting point will always be the paper of Gosling and Naim (2009), who tried to understand if it were true that agility was more indicated for ETO supply chains and leanness for STS ones, also attempting to overcome one important limit so far considered insuperable: the lack of reasoning related to applicability. In fact, all considerations were only related to theoretical studies and this can represent a limitation, in case of poor empirical researchers able to provide important clarification to confirm the theoretical proposition.

All researchers agree on some implementation possibilities, which can help improving the overall performance of ETO supply chains:

- Supply chain integration
- Information management
- Business system engineering
- Flexibility
- Time compression
- New product development process improvement

Until today far, ETO was considered as a unique homogeneous entity. Nevertheless, it incorporates a huge variety of sectors, in terms of products, characteristics, demand. The next part will try to address this important characteristic, in order to identify the variability of the industries contained. By the way, (Gosling and Naim, 2009)'s paper tried to address, as presented in Figure 3, the elements of commonalities and the ones of difference.



COMMONALITIES

1. Each product different from the previous and from the following;
2. Product dimensions completely customized;
3. Decoupling point located at the design stage.

DIFFERENCES

1. Design and technical characteristics of the products (size, shape, quantity).
2. Sector: for example, each construction project has always to be completed on a new site, whereas shipbuilding may take place at a fixed location.

Figure 3. Commonalities and differences between ETO sectors (Gosling and Naim, 2009).

As briefly introduced looking at the literature, ETO sector always appeared like a black box, not showing all those peculiarities and heterogeneities of its components. Therefore, this thesis will try to find a possible way to separate them, addressing the specific differences. Also considering that it is not valuable to identically consider businesses that differ in all aspects and only share high customization and low production volume (i.e., Shipbuilding and Capital Goods or Aerospace).

Furthermore, this work will not only try to open the ETO black box, but it will also seek to establish a connection with the previous paragraph related to supply chain management paradigms. The main idea is that separating the various industries would be possible to address if they individually can be related and improved by lean rather than agile techniques, or alternatively, despite all differences among the sectors, an unique and common strategy would be better to address and to provide insights for solving issues.

It is under the light of these elements that we look at I4.0, starting at the beginning with a more general viewpoint, ending with a selection of the most interesting technologies.

I4.0

Industry 4.0 is one of the most impacting trends of the current decades. It does not run out its effects only in manufacturing but has implications also in everyday life. Its final objective is to create a physical interconnected network able to unify humans with the environment and its objects.

The key enabler of this success lies in the ability to radically improve process performance, supporting the execution of activities, increasing the effectiveness of communication between actors and favoring data collection and sharing (Patrucco, 2020).

As a counterpart, the main problem is the difficulty to implement such technologies as they involve deep transformations in the way supply chain processes are executed (Patrucco, 2020).

Looking in its complexity, Industry 4.0 is a worldwide phenomenon that is embracing all aspects of the human society. It represents the fourth major disruption in modern manufacturing, after:

1. steam power;
2. mass production and outsourcing manufacturing phenomenon of the 1990s;
3. digital revolution and automation that took off in the 2000s (Fraga-Lamas *et al.*, 2016).

In history, all these revolutions brought diverse and severe changes and challenges for humanity. They were always supported by the governments (Hadjina and Matulja, 2018), which always played a crucial role.

According to Horváth and Szabó (2019):

What distinguishes I4.0 from the past is its ability to accumulate and synthetize the performance models of the previous revolutions

- All the four revolutions transformed one or more aspects of our life. Thinking at them as a sequence of events, each revolution added some element previously less considered. Conceived the first revolution as our starting point, it added the **energy aspect** to the initial business model in which only the **economic aspect** prevailed. The second industrial revolution added the **environmental aspect** and the third the **functional aspect,** till arriving to the fourth revolution where the added feature was the **social aspect**.

This brief summary is useful to introduce an essential consideration about I4.0. Clearly, it highlights the importance of the technological component, but in order to get a comprehensive picture about I4.0 it explains that it is necessary to embrace a wider point of view, also including social and political implications.

All the most important I4.0 technologies share a common departure point: the evolution and rapid development of Internet (Balkan, 2020). Internet enables the establishment of communication between people and machines. Furthermore, its widespread use ensures digitization in all areas, and production systems were the first entering into this process. Nowadays digitization has become a phenomenon able to permeate all the sectors, making it impossible for business to divide the new technological development from the digital world.

Summarizing some important concepts:

- Internet enabled the establishment of communication between people and machines
- Major developments in automation, sensor connections, data transfers, manufacturing systems technologies are some examples of information and communication technologies.

All these developments and changes in technology, also including ideas and theoretical approaches, take the name of Industry 4.0 (Karacay, 2018).

Now it is important to specifically focus on manufacturing, to understand how I4.0 is impacting the production processes. All the new technological systems that appeared in production in recent years are changing the industrial aspect (Balkan, 2020). New terms like smart factories, smart machines are daily used. They represent a real disruption, since they totally changed the conventional industrial systems and made possible the entrance of I4.0.

The concept of Industry 4.0 refers to a series of technological developments that affected and changed products and processes, with the result of integrating into production both the digital and physical world and enabling intelligent products to be produced. As the industrial appearance changes, smart product demand is rapidly changing, and more functional and comprehensive goods are being demanded (Benešová and Tupa, 2017).

The term “smart” is not just a simple adjective, it underlines a revolution that invests traditional enterprises and Industry 4.0 enterprises (Balkan, 2020).

The final objective of traditional companies was to provide high quality products or services to customers at the lowest possible cost. In addition, businesses were constantly aiming to increase their profits and their respectability. In this context, smart objects enter the scene. In particular, they allow to get various data about environment and process flow which are used to understand current operational situations and to solve errors (Saucedo-Martínez *et al.*, 2018). Existing failures can be corrected only after they are detected, maybe sending alarms to the management that can immediately intervene. Furthermore, in Industry 4.0 enterprises it is possible to use those data as input of the predicting process, in order to prevent and anticipate possible future errors. Thus, the management becomes more knowledgeable about the status of production lines and can solve the problem without error. The Industry 4.0 system targets zero downtime during just-in-time maintenance and production (Saucedo-Martínez *et al.*, 2018).

As previously introduced, I4.0 is not only a matter of technological developments. In this sense authors like Balkan (2020) were able to capture the importance of other global phenomena that triggered the emergence of Industry 4.0.
One of the most interesting is an economical and geopolitical factor, that is nowadays irreversible: it reflects the situation of the developed countries that are losing their leading role in relation to developing countries. This trend forced advanced economies to seek for a new production strategy, also due to the increase in social spending along with aging populations.

➔ The Fourth Industrial Revolution, forwarded at the initial stage by the United States and Germany, included the establishment of smart factories rather than manpower to increase production. For the first time man is losing is central role in production. Thus, according to Bartodziej (2017), the developed countries would be able to regain their lost competitiveness through smart factory installations.

Rebuilding the milestones that paved the street for Industry 4.0 (Balkan, 2020):

- The high-level developments in Internet after industry 3.0
- Technological developments
- The world's share of production that shifted from developed countries to developing countries, since the 1990s
- Population that increased in developing countries
- Costs that increased in developed countries, leading to a new revolution in production
- A new role for education system

About this last point, new emerging technologies are also affecting educationists. In the future humans will have to change their job, since all operational activity will be performed by smart machine. Anyway, they will still maintain an important role, since they will have to control and interact with the production systems. Therefore, their tasks will be more tactical, bringing benefits. Anyway, only the personnel well trained in the logic of new production systems can use these technologies. For this reason, enterprises should pay attention to human resources management and strategies and focus on the qualified development of the workforce (Lezzi, Lazoi and Corallo, 2018).

Figure 4 synthetize the complexity of the environment that allowed Industry 4.0 to arise and develop.

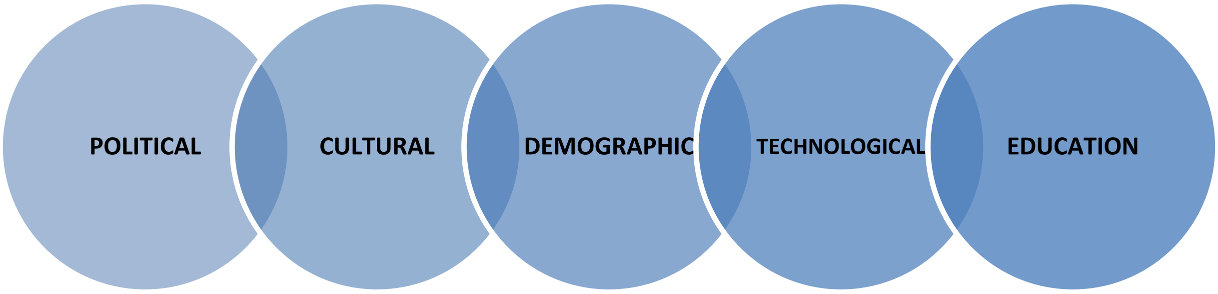


Figure 4. Elements that triggered the emergence of Industry 4.0.

The last part will be dedicated to other two key resources of I4.0: data and cloud system (to storage data). The demand of this new resource is dramatically increasing year by year. Therefore, investments in this virtual structure are needed. In addition, in terms of information technologies, specialized personnel able to implement the cloud system in enterprises will become fundamental, both with experts who will enable the integration of the cloud system engineers (Balkan, 2020).

Considering also this final section, Karacay (2018) provided an interesting definition of Industry 4.0 that in some way collect all the information we previously discussed. He said that with Industry 4.0 new business environments are emerging, where the machine-human-product relationship between smart factories is established with the internet and where the work is carried out on the internet and the target productions are planned and executed efficiently by robots.

TECHNOLOGIES – ADDITIVE MANUFACTURING

This paragraph introduces the main technology that will be analyzed in the following chapters. Therefore, this introduction does not result in a mere generic list of the entire spectrum of Industry 4.0 technologies. Indeed, only the one that comprehends a transversal implementation across Aerospace, Machinery and Shipbuilding will be taken here into consideration. Already at this initial stage there is the willingness to capture its main features, with a more precise look at those that will be deepen during the analysis of the sectors. All the other technologies will be treated when encountered scrolling through the chapters.

Generally speaking, additive manufacturing (AM) is the "process of joining materials to make objects from 3D model data, usually layer upon layer" (Diegel, Nordin and Motte, 2019a). Starting from this definition, two specific characteristics stands out:

- ✓ AM is the specific process that allows to fabricate objects directly from the virtual CAD data, by adding material (such as metals, polymers or ceramics), (Atzeni and Salmi, 2012);
- ✓ Unlike the most traditional manufacturing processes, AM is additive rather than subtractive. The parts are constructed by adding material layer by layer to form the net shape with a variety of materials that can be used in the process (Togwe, Eveleigh and Tanju, 2019).

Evolving from rapid prototyping in the late 1980s, additive manufacturing has emerged as a powerful facet of advanced manufacturing (Gibson, Rosen and Stucker, 2015). The American Society of Testing and Materials (ASTM) defines AM as follows: AM is "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies". Possible synonyms that will then be used during the continuation of the thesis: 3D printing, additive fabrication, additive process, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication" (Strong *et al.*, 2017).

What can be added to AM definition and its main features is a consideration regarding the implementation phase of AM. It could result to be complicated, since it would not only affect the current working methodologies, but the supply chain in its entire aspects. Thus, the decision of introducing such technique can't be merely taken by one actor of the chain, since it would affect also suppliers and other stakeholders. Tuck, Hague and Burns (2007) understood this criticality and tried to discuss how AM technology would be able to change supply chain management thinking.

Collecting major benefits and drawbacks of AM application:

Major benefits

- ✓ AM provides the capabilities to process a *growing range of materials* and produce parts with *complex geometries* in a smaller batch size without additional time and costs;
- ✓ J., Irene, P. and Simpson, T. W. contended that AM can localize production and sourcing activities, although highlighting the need for finishing and post-processing activities (e.g., heat treatment) to achieve functional tolerance and part performance for a widespread adoption;
- ✓ Walter, Holmström and Yrjölä (2004) asserted that a centralized and decentralized applications of AM using a **decision support model** can help supply chain managers to better capture emergent business opportunities related to AM, with particular reference to its capability to produce highly customized parts (Cheng and Nee, 2015).

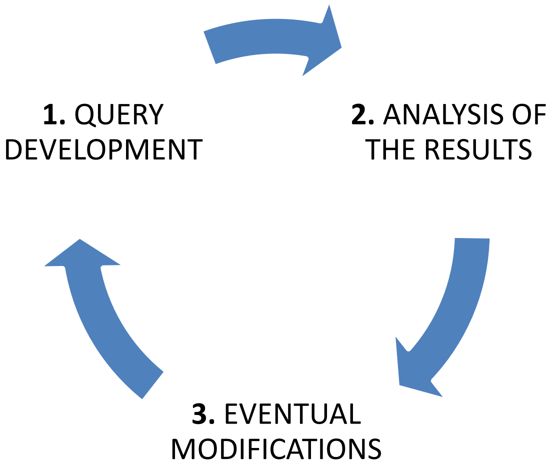
Main drawbacks

- × The major drawbacks of AM are mainly related to the significant initial investment costs, to the cost of materials, to the challenges to scale up to mass production and to a lack of awareness about how to fully exploit the advantages of AM (Wohlers, 2015). This last criticality is also highlighted in the work of Munguía, De Ciurana and Riba (2008), where it is explained that the risks associated to the high initial costs and to the lack of best practices can hinder the transformation and implementation of AM;
- × The AM capabilities to provide an ever-growing range of materials and produce parts with complex geometries has, as counterpart, the production of parts which have poorer surface finish and accuracy (Diegel, Nordin and Motte, 2019b);
- × Besides high costs, other major obstacles of AM processing are: slower speed, addition complexity for re-engineering and willingness of OEMs to re-engineer their products (Khajavi, Partanen and Holmström, 2014).

METHODOLOGY

This part will be devoted to the explanation of the criterion used for including papers in the review. Key-word searches were made through several databases including among all Google Scholar, Scopus and Science Direct, which enabled to access all the different articles, abstracts and citations. In order to decide which keywords to use in the search engines, it was important first of all to develop a strong query. Therefore, the first task of the thesis was to understand the best way to search the papers to be consulted.

It was done following an iterative process that had the objective to understand step by step possible improvements or modifications of the query, that were added immediately:



At the initial stage, it was essential to find a query able to catch the two main souls of the thesis:

- the sector of application, in this case the Engineer-to-order sector
- the innovation and technology brought by the Industry 4.0

Therefore, the terms “supply chain” with “ETO” (and all its different variants like “Engineer-to-order”, “Engineer to order”), combined with the keyword “Industry 4.0” were initially considered. The idea was to remain as general as possible, in order to initially frame the field of study and become aware of it.

QUERY

("Supply Chain" OR "SC") AND ("Engineer to order" OR "Engineer-to-order" OR "ETO") AND ("digital*" OR "Industry 4.0")

RESULT: 14 articles

The result was not satisfying, and the cause was the term “supply chain”.

Terms which were putting the query out of focus, like “Evapotranspiration”, were deleted.

QUERY

("Engineer to order" OR "Engineer-to-order" OR "ETO") AND ("digital*" OR "Industry 4.0") AND NOT "evapotranspiration"

RESULT: 55 articles

The next step was adding the most famous I4.0 technologies, as "Big data", "Data analytics", "Internet of things", "Blockchain", "Cloud computing", "Cloud manufacturing", "Advanced robotics".

QUERY

("Engineer to order" OR "Engineer-to-order" OR "ETO") AND ("digital*" OR "Industry 4.0" OR "Big data" OR "Data analytics" OR "Internet of things" OR "Blockchain" OR "Cloud computing" OR "Cloud manufacturing" OR "Advanced robotics") AND NOT "evapotranspiration"

RESULT: 69 articles

Eliminating “emitter turn-off” → *Result*: 59 articles

The result of 59 documents was not still satisfying, both in numerical and qualitative terms. In fact, it was difficult to identify interesting common patterns in articles the were too different between each other, due to a problem of high variance of the sectors.

So far, the query development process was not sufficient to guarantee a solid basis of articles. Then a new idea came out, related to the possibility to split the overall engineer-to-order reality into its various sectors, studying them separately and combining just in the end, to provide a more comprehensive picture. Therefore, the “ETO” keyword was substituted by a combination of “Supply Chain” and five of the most important sectors of ETO:

1. “Oil and gas”
2. “Engineering, Procurement, Construction”
3. “Shipbuilding”
4. “Aerospace”
5. “Capital goods”

The fundamental step now was to decide an analogous path for all the industries in order to come up with a standard model. It was important in an optic of re-matching of all the sectors in one unique final query. Therefore, since it was possible to proceed with an analogous path, only oil ang gas (o&g) will be explained:

QUERY
("Supply Chain" OR "SC") AND ("oil and gas" OR “oil&gas” OR “o&g”) AND ("digital*" OR "Industry 4.0")
RESULT: 34 articles

To come to the final query, all the different I4.0 technologies were added:

QUERY
("Supply Chain" OR "SC") AND ("oil and gas" OR “oil&gas” OR “o&g”) AND
("digital*" OR "Industry 4.0" OR "Big data" OR "Data analytics" OR "Internet of things" OR "Blockchain" OR "Cloud computing" OR "Cloud manufacturing" OR "Advanced robotics")
FINAL RESULT: 41 results, 8 articles

Exactly in the same way of o&g, also all the other sectors were studied with the identical structure of the query, with the following results:

- **EPC**: 125 results, 41 articles
- **Shipbuilding**: 5 results, 4 articles
- **Aerospace**: 102 results, 25 articles
- **Machinery**: 127 results, 20 articles

If the reasoning were correct, theoretically the sum of all the articles related to the sectors taken separately would have been equal to the result of a unique query that included as key-words all the industries together: the result was to consider all the sectors combined just in a unique query. The important element we had to take care of was checking if articles were not lost in this operation.

After having compared that the sum of all these sectors taken separately were close to the result of including them all in just one query, we could assess that the result was correct. In fact, the general query differed from the total sum just by 3 articles: 87 against 90. Few articles overlapped.

Hence, the **definitive query** was deployed:

("Supply Chain")
AND
("oil and gas" OR "oil&gas" OR "o&g" OR "EPC " OR "Engineering, Procurement, Construction" OR "Engineering-Procurement-Construction" OR "Construction Industry" OR "Building Industry" OR "ship building" OR "shipbuilding industry" OR "shipbuilding sector" OR "merchant ship" OR "aerospace" OR "aircraft" OR "aviation" OR "Machinery" OR "Capital goods" OR "Machine tool")
AND
("digital*" OR "Industry 4.0" OR "Big data" OR "Data analytics" OR "Internet of things" OR "Blockchain" OR "Cloud computing" OR "Cloud manufacturing" OR "Advanced robotics")
AND NOT “agricult*”)

RESULT: 375 results, 95 articles

In this last query all possible technologies were included, taking inspiration from the book “A Roadmap to Industry 4.0: Smart Production, Sharp Business and Sustainable Development”, written by Anand Nayyar and Akshi Kumar. Here the “Technology pillars of Industry 4.0” were widely described and we took inspiration to add some other technologies previously neglected. The result was an addition of:

1. “building information model”
2. “additive manufacturing”
3. “augmented reality”
4. “wearable technology”
5. “artificial intelligence”

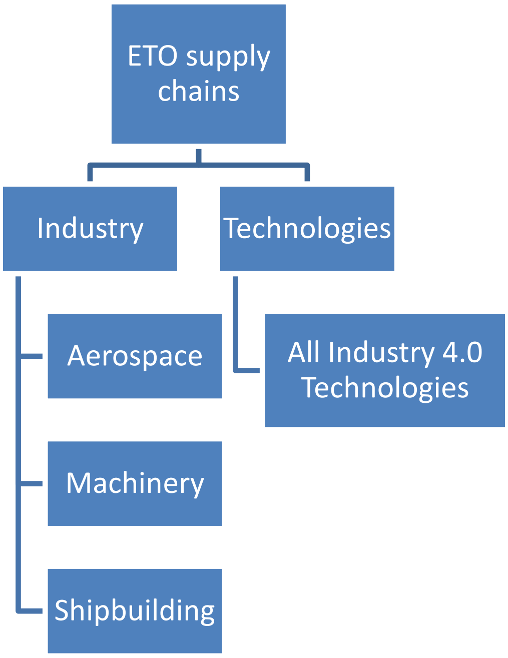
6. “machine learning”

The query gave 375 documents and 95 articles.

We decided only to take into consideration the articles, since they are more complete and this is a theme still not deeply threated. In order to determine the perceived quality of the journals in which the papers appear the Association of Business Schools (ABS) ‘Academic Journal Quality Guide’ (Harvey et al., 2007) has been utilized. Then, studying the abstracts, it was possible to identify which among these articles were not related to the research, coming up to **58 articles**.

Only three sectors were taken into consideration, since they were those ones with the more numerous articles that resulted interesting. From them I started my literature review.

The thesis will be divided in three sections, according to the three industries I analyzed: Aerospace, Machinery and Shipbuilding.



RESULTS

This chapter contains the analysis split into the three sectors analyzed. A common structure follows: a first introduction part that can refer generically to the sector (like in Construction and Shipping) or can be specific to a precise field (like Aerospace). Then, it will be followed by a detailed analysis, different for each industry, trying to highlight the relationship with Industry 4.0.

AEROSPACE

Intro – the problem of Spare Parts in Aerospace Industry

In this chapter, Aerospace is not analyzed in its entirety but on a specific aspect that characterizes it and make it peculiar: spare parts supply chain. The decision to perform a very specific analysis, not considering the sector in general way (like in Chapter 3.2 and 3.3), is due to different motives:

- First of all, many reliable publishers' papers treated in detail the topic, giving a very large amount of valuable information;
- then, this theme is central for the whole industry and all companies have to deal with it. Therefore, field of application is very large and open to future discussions;
- finally, this topic easily lend itself to the new technologies of Industry 4.0, making easy to discover possible connections, discovering weaknesses and benefits gained with their implementation.

Generally speaking, spare parts management has always represented for manufacturing industries one of the most widespread challenge. Aircraft stands out as one of the main affected, both due to external factors and to some intrinsic characteristics. As (IATA, 2011) pointed out, the increase in competition in worldwide air traffic, sided by the growth of high quality and safety standards, brought an always increasing pressure on aircraft supply chains concerning the availability of spare parts.

The main objective of spare part inventories is:

1. serving the defective or preventive maintenance planning
2. fulfilling the demand for parts that fail or are likely to fail (Gu, Zhang and Li, 2015)

In the specific case of Aircraft, the demand of spare parts is unpredictable and non-stationary, due to their large volume and high value (Simao and Powell, 2009). Conventionally, firms must invest heavily in their spare parts supply chain operations, in order to reach high fulfillment and reliability rates (Khajavi, Partanen and Holmström, 2014).

This inevitably leads to some issues like high warehousing and obsolescence costs, since it requires a large number of inventories to be close to the locations of consumption (Khajavi, Partanen and Holmström, 2014).

As an instance, Airbus maintains a 36,000-square meter warehouse for spare parts in Hamburg, Germany (Togwe, Eveleigh and Tanju, 2019). Such huge dimension is a consequence of the several millions of parts that a commercial airplane is made of. Although the majority of the parts is infrequently needed, they have to be kept in stock in order to ensure fast service time (Liu *et al.*, 2014). Furthermore, spare parts are characterized by a high risk of obsolescence and high shortage costs (Holmström and Partanen, 2014). It also applies to those companies that are along aircraft spare parts supply chain, which face significant challenges in providing fast repair and maintenance services, while minimizing costs (Liu *et al.*, 2014).

To gain a comprehensive overview over spare parts in Aerospace, the next paragraph will take into account both financial and operational implications, ending with an analysis related the main demand features. Focusing on demand is crucial, since it is the uncertainty that companies face at this stage that affect and threaten the remaining supply chain structure. Furthermore, the obtaining of an exhaustive picture of the phenomenon will be easier the comprehension of possible connections with Industry 4.0 technologies.

Therefore, the analysis is broken into three main levels:

1. *Impact on costs*

   The efficient management of spare parts has strong cost implications, in particular in a sector like aircrafts, where companies are forced to hold a significant amount of spare parts inventories (Syntetos, Babai and Altay, 2012). Just to provide some real cases, the United States (U.S.) Military reported a spending of $194 billion on logistics operations and its spare parts supply chain, with $104 billion spent on supply, $70 billion budgeted for maintenance, and $20 billion budgeted for transportation (Khajavi, Partanen and Holmström, 2014). Furthermore, it is estimated that for the commercial airlines over $40 billion of spare parts inventory is tied up in capital, (Basten and van Houtum, 2014).

Choosing the level of inventories for spare parts has key implications both in terms of efficiency and in terms of effectiveness, as shown in Figure 5 (Gu, Zhang and Li, 2015):

Efficiency

- An excessive stock levels of spare parts would result in exorbitant holding costs, increasing the risk of cash flow impediment.
- Still, there is another factor it is important to take into consideration: obsolescence. Innovation could make the spare parts most infrequently used obsolete, with the result of increasing inventory costs to maintain in stock something useless.
- To gain an idea of the magnitude of the phenomenon, the U.S. Navy estimated the annual obsolescence cost equal to $750 million. During a recent conflict, the Osprey V-22 program had 12 aircraft deployed and spare parts for 36 aircraft on hand; however, only 13% of those parts were needed.

Effectiveness

- Effectiveness: a possible shortage of stock would lead to poor cycle service levels (CSLs), lack of reliability and, consequently, poor overall supply chain performance.
- The last point is linked to the above concept of maintenance, repair, and operations (MRO), which brings the customer at the center of the value generating process.
- Companies now have to provide a high service level keeping at the same time costs under control. Therefore, the cycles of maintenance, repair and overhaul services in Aerospace have been significantly challenged in an optic of costs minimization.

Figure 5. Principles of Efficiency and Effectiveness (Gertler, 2011), (Huang *et al.*, 2013), (Huang *et al.*, 2013)(H. Khajavi, Holmström and Partanen, 2018)

Therefore, aircraft manufacturers have to be at the same time effective and efficient, able to match demand and supply, providing much-needed components at the lowest possible cost, (Gertler, 2011). In addition, researches like the one of (Liu *et al.*, 2014) demonstrated that Aircraft spare parts demand pattern follows the Pareto curve. It means that 80% of the parts are needed frequently and make up most of the airline demands. However, they only account for 20% of the supply chain expenditure in terms of holding inventory and moving materials. In other words, the majority of the supply chain cost is due to the small amount of slow-moving parts. The spare parts supplier often subsidizes the holding cost of these parts with the profits they make from the fast-moving spare parts.

To synthetize the paragraph related to the costs:

- High stock levels of spare parts result in excess holding costs, increased risk of obsolescence costs and cash flow impediment (Huang *et al.*, 2013),
- while shortages lead to poor cycle service levels (CSLs), lack of reliability and, consequently, poor SC performance (Gu, Zhang and Li, 2015).

2. *Impact on operations*

At this level the complexity of spare parts management is analyzed in terms of operations, looking at suppliers' relationships and process lead time.

2.1 Supplier

The unpredictability of the demand of spare parts destabilizes the business of long-term suppliers. The main issue is related to the short life cycle-driven environment, which could make obsolete even spare parts that are being producing in the specific moment, for example in case of older versions of aircrafts (Ghadge *et al.*, 2018). This strongly effects the overall management process.

2.2 Lead time

It is one of the most critical challenges for Aerospace industries. Analyzing the current conventional process, the manufacturing lead time can even reach several months. On the other hand, the aircraft spare parts industry requires a very high cycle service level (CSL) to meet customer demands (Liu *et al.*, 2014).

Therefore, companies are forced to keep a high level of safety inventory in order to cope both with the long procurement lead time and the high CSL, with the result of a significant driving up of the costs of the supply chain (Liu *et al.*, 2014).

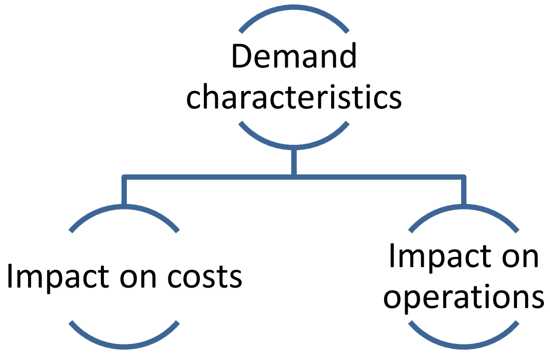
3. *Demand characteristics*

According to Regattieri *et al.* (2005), the demand for spare parts arises when a random component failure occurs or when components are subjected to preventive maintenance during their lifespan. In aircrafts it is highly intermittent and strictly linked to concepts of traceability (for safety reasons) and high out-of-service (for grounded aircrafts).

In addition, it is possible to add some other recurrent demand features:

- → Many aircraft spare parts have high value, are infrequently ordered and require long replenishment lead time (Basten and van Houtum, 2014)
- → Demand is often affected by stochastic factors such as:
  - ✓ wear behavior, which usually depends on the phase of the aircraft's lifespan (initial, maturity or end of life phase),
  - ✓ type of maintenance,
  - ✓ failure rates (Lowas and Ciarallo, 2016), which can either be constant or dynamic (Basten and van Houtum, 2014).
- → Demand can be influenced by the variability of aircraft locations, as they keep moving across the globe. Consequently, the maintenance companies need to estimate the optimal stock level at various hubs (airports) in the network (Fritzsche, 2012).

The three levels just analyzed are all parts of the same picture, they influence each other and are strictly connect.



For instance, all problems in operation and all costs are expanded in case of demand unpredictability, which creates forecasting difficulties, especially for new products whose data about failure rates are still unavailable (H. Khajavi, Holmström and Partanen, 2018). Now, a brief representation about the current functioning of aircraft spare parts supply chains will follow. This will illustrate the as-is situation, with current management methods and existing technologies. After this analysis, the to-be situation will follow, introducing for the first time the concept of Industry 4.0.

Liu *et al.*, (2014) provide a perfect picture of the actual spare parts supply chains in aircraft industry. They take into account as key indicator the *frequency of usage* of the spare parts. According to this value, spare parts have to be managed in two totally different ways:

FREQUENCY OF USAGE	**MANAGING WAY**
Standard Replacement Parts	The safety stock of standard replacement parts is managed in-house through airline warehouses. These parts can be ordered at regular intervals according to a maintenance plan.
Less-frequently-used Parts	They are purchased from suppliers and often require a 24h delivery time to ensure fast service. - Therefore, suppliers must keep these parts in stock and use an overnight delivery service. - At the same time, the stock of the most infrequently used items must be kept as low as possible. One typical strategy can be to aggregate demand using central warehousing, however negatively impacting on delivery costs.

Independently from the frequency of usage, a common issue that companies have to face is related to the current limitations of production technologies that oblige to produce large batch size in order to take advantage of economies of scale. Focusing on slow-moving parts, it translates in longer lead time and a larger amount of capital tied up in the form of inventory.

- The to-be situation

Predictions about the future show a stronger and stronger influence of Industry 4.0 (I4.0) technologies on the overall Aircraft sector. I4.0 has the potentially to transform and completely rethink the actual spare parts management strategies, revolutionizing the role of all the actors involved. As different authors like Khajavi, Partanen and Holmström (2014) pointed out, the new trend regarding the *digitalization* phenomenon of spare parts process can result both in:

- a strategic opportunity (Wise and Baumgartner, 1999)
- a threat

This reflects the fact that for many original equipment manufacturers, the focus of the competition is increasingly shifting away from the price and quality of the offerings, towards the delivery of value to customers (Vargo and Lusch, 2014). In this case the customer value is related to ability to keep the products reliable and always available.

Maintenance, repair and operations (MRO) is closely tied to the making accessible the appropriate parts and skills whenever the demand manifests, thus satisfying the needs of customers and reducing downtime costs (Khajavi, Partanen and Holmström, 2014).

Here digital manufacturing technologies enter the scene, promising to resolve (Holmström *et al.*, 2010) the major challenge connected to the ability to provide the necessary parts with high fulfillment rates and at low costs (Zanoni, Ferretti and Zavanella, 2005).

This brief intro is the prelude of a more complete analysis regarding how the new technologies born in the fourth industrial revolution domain can disrupt the as-is situation of spare parts management. Specifically, Additive Manufacturing (AM) will be presented like one of the answers to the criticalities faced by the industry. Thus, two sessions will follow:

1. A first analysis linked to AM in general, which will address why this specific technology is suitable to solve the issues previously listed.
2. Then, a more specific overview which will involve the main advantages and disadvantages carried by the AM application in aircraft industry.

The solution of I4.0 for spare parts: Additive Manufacturing

In this chapter Additive Manufacturing (AM) is introduced as one of the most promising technologies able to solve spare parts inventory management challenges, faced by Aviation. First of all, a brief recall of the definition used in the introduction part: AM is the "process of joining materials to make objects from 3D model data, usually layer upon layer" (Diegel, Nordin and Motte, 2019a). Now, all the main ideas from literature will be introduced.

In this regard, many manufacturing industry experts assume that AM will soon be able to overcome the existing technological bottlenecks, with the result of taking the place of the current adopted techniques (Joshi and Sheikh, 2015). To support this evidence, in aircraft and automotive industries, AM already managed to produce low-weight components (Joshi and Sheikh, 2015), providing also higher safety standards and improving the overall aircraft SC dynamics. As an example, Boeing recently used selective laser sintering technology to produce thermoplastic spare parts for its commercial 737, 747 and 777 aircrafts (Weller, Kleer and Piller, 2015).

Actually, excepting for the successful example of Boeing Rockedyne, in which parts for the F-18 fighter aircraft and the International Space Station (Holmström *et al.*, 2010) were included via AM, still there is no widely adopted approach able to support AM in the aviation spare parts network (Holmström *et al.*, 2010). There are examples of references that try to address advantages related to AM, (Thomas and Gilbert, 2015), but they are still few cases. Therefore, this literature will now be analyzed to capture the most developed insights, also to settle if researchers view Additive Manufacturing like a disruption technology.

In this sense, first of all it is important to provide an answer to the last question. About it, the most common opinions are well synthetized by the papers of Liu *et al.* (2014) and Khajavi, Partanen and Holmström (2014). They are interesting since they perfectly represent the two possible positions that researchers have taken in the latest years, related to the eventual potentiality for AM to fix spare parts problem.

FAVORABLE	UNFAVORABLE
According to Liu *et al.* (2014), AM technology can change the traditional configuration of the supply chains of different industries, enabling the opportunity to manufacture parts on demand, which would reduce the need of maintaining safety inventory, with the final aim of improving supply chain dynamics. This is especially useful in the aircraft spare parts industry where currently there is a need to maintain a high level of safety inventory for high-cost long-lead time metallic parts. Therefore, more and more companies in the aerospace industry are interested in using AM technology.	For authors like Khajavi, Partanen and Holmström (2014), instead, it is not the actual best suitable technology, although it is able to answer to one of the typical objectives in spare parts inventory management: maintaining an appropriate level of spare parts inventory to ensure system availability and cost effectiveness by not carrying an excessively large inventory (Aisyati, Jauhari and Rosyidi, 2013).

FAVORABLE

To support the reasoning introduced by Liu *et al.* 2014), a small diagram is presented. Starting from the technological characteristics of AM it will be possible to understand how it impacts on operations, and finally to include considerations about implementation drawbacks or benefits. In this way, it is possible to make a connection between AM characteristics and the advantages or disadvantages brought by AM in Aircraft industry, also in monetary terms. Then, the most interesting concepts will be briefly deepening.

TECHNOLOGICAL CHARACTERISTICS	***OPERATIONAL IMPLICATIONS***	***BENEFITS/ DISADVANTAGES***
AM technology offers two opportunities, (Liu *et al.*, 2014): (1) redesign products with fewer components, (2) directly transform computerized 3D models into finished products, without the use of additional fixtures and cutting tools.	Through the usage of fewer components and 3D models, AM technology has the potentiality to improve supply chain dynamics by, (Liu *et al.*, 2014): - shortening delivery lead times, - manufacturing product near to the customers. ->> As a result, shorten manufacturing lead time.	✓ shipping costs drop, ✓ avoidance of high material and resource wastage factors, ✓ packaging, transportation and warehousing costs reduction ->> More in general, reduction of the number of stages in the traditional supply chains.
AM introduces new design capabilities if compared to traditional manufacturing technologies, (Lindemann *et al.*, 2012). This property can be called *design flexibility*.	*Design flexibility* allows a weight reduction up to 80%, and fewer materials usage. Therefore, AM is considered a *"lean"* approach (Togwe, Eveleigh and Tanju, 2019). These parts will maintain the same functionalities. ->> This property takes the name of *Lightweighting* (Carter and Erno, no date).	*Lightweighting* in aviation results in real and tangible benefits during the utilization stages, as it enables: ✓ fuel savings ✓ greater weight to be apportioned for mission critical cargo, (Carter and Erno, no date).

In case of AM, raw materials are invented to be fungible or replaceable so that it is not fundamental the equity of a 1:1 ratio with the anticipated saved parts.	AM enables higher flexibility thanks to new raw material quality (i.e, substitutability), differently to traditional manufacturing.	The fungibility of raw materials allows to reduce quantities and costs.
An important feature of AM consists in its functionality. Through slowly changing the material composition, the layers are not easily removable since they are stuck, pasted, (Togwe, Eveleigh and Tanju, 2019).	Thanks to this functionality, it is possible to reach the desired quality, reduce the complexity of processing and the time needed to reach the characteristics wanted.	This benefit is very effective in Aerospace because each element is continually covered with resistant parts that avoid damages and costs of production waste. They are long-term elements built with this strategical technique.

- Briefly recalling the operational implications of *lightweighting*, it includes fewer material usage in relation to traditional manufactured designs, making AM a **"lean"** approach (Togwe, Eveleigh and Tanju, 2019). Such approaches are gaining more and more popularity in Aerospace industry, due to the operational simplicity and the clear financial savings, sided by reducing waste processes. In particular, AM is a near net shape process, therefore it can enable raw material cost savings over traditional parts, (Dehoff *et al.*, 2013).
- As previously discussed, *Agility* is among the most interesting AM capabilities, representing one of the key reasons why the Federal Aviation Administration (FAA) selected this technology, rather than other traditional processes, which require molds or complex fixtures, (Tuck, Hague and Burns, 2007). As General Electrics noted, it allows iterative design changes to be made at negligible cost to the project schedule.

- Linked to the previous point, AM technology can cost-effectively produce even *small batches* of parts, that usually require higher costs, if related to the consequent loss of economies of scale. As a result, it has also the potential to reduce the need of safety inventory. Since AM only requires 3D data and raw materials in order to produce complex parts, it will also reduce setup, changeover time and the number of assemblies (Liu *et al.*, 2014). For all these reasons, many aircraft manufacturers are already using AM technology to produce high-cost long-lead metallic components (Liu *et al.*, 2014).

To complete this paragraph related to the benefits of AM implementation, it is interesting to introduce a particular index that different authors consider really suggestive, the "*buy to fly*" ratio. It is the ratio between the raw material used for a component and the weight of the component itself (Allen, 2006). This ratio is commonly used in the aerospace sector and is perfectly suitable for the AM technology, which would lead up to a 70 per cent potential reduction in the original weight of part (Baumers *et al.*, 2016).

UNFAVORABLE

To gain a comprehensive overview about AM technology it is also necessary to study its main criticalities. In literature, diverse reviews suggest

- machine acquisition price,
- and personnel intensiveness

as some of the major obstacles to a distributed deployment of AM in spare parts supply chains (Khajavi, Partanen and Holmström, 2014). These elements become even more important in Aviation, where there is an additional problem related to the size of the machine build chamber, with higher costs for training the personnel (Lindemann *et al.*, 2012). Therefore, it comes up that the strongest barriers for the adoption of AM are related to the costs of acquisition and those of operations, like utilization, energy consumption, etc. (Thomas and Gilbert, 2015).

Focusing on the comparison between an aluminum alloy part made by laser sintering typical of AM and classical die casting, it resulted that AM's material cost is approximately 10 times higher, leading even to an overall cost 25 times more expensive (Atzeni and Salmi, 2012).

Furthermore, some other limitations regard the implementation phase, such as quality issues and, more in general, a lack of globally accepted quality standards for the manufactured parts (Weller, Kleer and Piller, 2015).

Especially from a safety point of view, AM still needs a considerable amount of research before achieving a reliable standard. The raw materials available for AM do not always match the characteristics of CM processes (Conner *et al.*, 2014). The manufacturing throughput speed is relatively low, and quality control standards have been initiated but not fully established (Weller, Kleer and Piller, 2015).

DISADVANTAGE MITIGATION

Given the main criticalities, it is also possible to find in the literature researches whose main aim was to find possible solutions to overcome the main barriers represented as example by costs.

- As Thomas and Gilbert (2015) pointed out, the average inflation-adjusted cost of AM machines decreased by 51% from 2001 to 2011, and various approaches to low-cost metal powder material production are also being pursued (Syntetos, Babai and Altay, 2012).
- For other authors it is even not fair to evaluate this technology using just cost-based considerations. For example, the notion of cost versus value has been discussed previously, with researchers proposing that it is crucial to consider the 'added value' introduced by a technology rather than focusing on 'added cost' (Zhu, Mukhopadhyay and Kurata, 2012).
- Therefore, according to these authors the visible costs of a metal part fabricated via AM has become comparable with the cost of a traditionally fabricated part using machine, material, and personnel cost categories in combination with such techniques as activity-based costing.

From all these different viewpoints, it is possible to conclude that costs represented the main barrier between the critical aspects of this new technology, but it is a phenomenon contrastable globally. From the point of view of these authors the value of inflation- adjusted cost of AM machines is decreased by 51% from 2001 to 2011, and more approaches economic materials pursued. Instead, other authors think the added value of this technology is a more influent aspect to consider rather than the costs. In conclusion, AM technology will soon be comparable to traditional factory for the costs used for machines, materials and personnel represents the difference.

Implementation of AM

So far, we discussed about benefits and disadvantages from a theoretical viewpoint. The next stage instead reflects another aspect of Additive Manufacturing not yet taken into consideration: the implementation phase. AM is a technology that is really difficult to deploy. As we guessed in the previous paragraph, all the actors of the chain have to be involved in case of adoption of AM technology, since it can even affect the geographical location of suppliers or the cultural characteristics of the company.

With this objective, the researches of Liu *et al.* (2014) and Khajavi, Partanen and Holmström (2014) are analyzed. They present different ways for AM to be implemented in Aerospace industry, in relation to spare parts management.

- Khajavi, Partanen and Holmström (2014) studies the AM implementation in supply chains with a real-world case, setting a scenario model of the F-18 Super Hornet environmental control system. It is one of the earliest and most well-publicized deployments of AM technology for functional product manufacturing, able to illustrate the trade-off between costs and technology requirements. The spare parts supply chain of the F-18 Super Hornet fighter jet was selected since the air-cooling ducts of the environmental control system were produced using AM technology.

- The purpose of the research of Liu *et al.* (2014) is to analyze the impact of AM in the aircraft spare parts industry, trying to address possible implementation strategies able to decrease the overall costs. This investigation provides guidance for the development of additive manufacturing machines in spare parts supply chains. According to Liu *et al.* (2014), there are two main possibilities for implementing AM, through a centralized and a decentralized way. It will be analyzed which of these two approaches would be more feasible to be applied to Aircraft industry.

The following chart summarizes the three most critical implications that are affected by a decision to centralize rather than to decentralize: aggregation of the demand, lead time and production costs.

CENTRALIZED	**DECENTRALIZED**
✓ Demand aggregation × High lead time	✓ Low lead time × High production costs

1. The first approach consists in *centralizing* AM capacity, through the creation of specific locations where it is possible to produce spare parts.
   - ✓ The most important result of this solution is the aggregation of the demand from various regional service locations, ensuring in this way a saturation of AM capacity, spreading the high fixed costs on higher production volumes.
   - × The main disadvantage is the higher lead time, since the produced parts have to be shipped to the service locations. In addition, for specific parts that are needed in the first-line maintenance, inventory still needs to be carried to the service locations.

   This approach is preferred in case of low demand of spare parts produced via AM, and when the lead time is not a critical factor.

2. The second approach consists in distributing AM capacity among the multiple service locations.
   - ✓ This solution allows, from one hand, to reduce significant costs like transportation and inventory holding and, from the other, to provide benefits in terms of operations, allowing to decrease the overall lead time.
   - × On the contrary, other costs arise due to the duplication of resources and the loss of demand aggregation.

   This approach is suitable when the demand of AM producible parts is sufficiently high to justify the capacity investment or when it is needed a faster response time.

In order to assess which of the two approaches is more fungible in Aviation, the different scenarios are investigated (including also the current situation as a starting point), and their performance are analyzed in terms of required safety inventories (Liu *et al.*, 2014):

- Conventional (as-is) supply chain
- Centralized AM supply chain

- Distributed AM supply chain

The first case is related to the reference scenario. It refers to traditional technologies and working methods. It is based on the spare parts suppliers' current practices that can be improved through the application of Additive Manufacturing (Khajavi, Partanen and Holmström, 2014). The second and third ones refer to the two approaches previously discussed: centralization vs decentralization. The scenarios are compared taking into consideration factors like demand characteristics, manufacturing lead time, logistics lead time total operating cost, and downtime cost.

As a preliminary result, through a case study based on data obtained in the literature, Liu *et al.* (2014) was able to demonstrate that the use of AM can bring various opportunities, like changing the conventional configuration and achieving safety inventory reduction. This would allow to cut inventory holding cost across the entire supply chain.

→ Therefore, it is immediately possible to remove the first scenario and discuss only the Additive Manufacturing implementation.

Anyway, AM technology can be introduced into different stages of the aircraft spare parts supply chains, and this can become a discriminant point for the choice of centralized and distributed implementation.

According to Liu *et al.* (2014):

- The centralized AM supply chain is more suitable for
  - parts with low average demand,
  - parts with relatively high demand fluctuation,
  - parts with longer manufacturing lead time.

- The distributed AM supply chain is suitable for
  - parts with high average demand,
  - parts with very stable demand, (in this case the benefit of demand aggregation in a centralized distribution center is greatly diminished),
  - parts with very short manufacturing lead time (even if their demand is low and unpredictable, since such parts can anyway be produced on-demand),

Moreover, a distributed logistics operator may decrease the need for 3PLs (third-party logistics providers) and freight forwarders, as there will not be the need to transport parts around the globe, as previously.

Also Khajavi, Partanen and Holmström (2014) made an analogous analysis, modelling a scenario of a real-life spare parts supply chain in the aeronautics industry. The goal was always trying to evaluate the potential impact of additive manufacturing improvements on the configuration of spare parts supply chains. According to this study:

- the centralized production was the preferred supply chain,
- however, distributed spare parts production can get practical as AM machines become less capital intensive, more autonomous and offer shorter production cycles.

This suggests that the higher automation, lower acquisition price and shorter production time are the factors that the producers of these machines should aim to develop to enable radical change in spare parts supply chain operations (Khajavi, Partanen and Holmström, 2014).

MACHINERY

In this chapter, the influence of Industry 4.0 over *Machinery* will be evaluated, with all its implications.

Intro - the importance of data

Although machinery has always been considered as a strictly traditional sector, in the latest years it is facing a profound phenomenon of digitalization, which is rapidly transforming it into a smart manufacturing system. Actually, capital goods industry constantly embraced technology, but it was mainly focused on the physical manifestation of manufacturing technology, leaving little emphasis on the 'cyber' side, like *Data Analytics* (Lenz, Wuest and Westkämper, 2018). Hence, it is still common to find a skill gap when manufacturing workers have to adopt a more data-centered mindset.

Anyway, such digitalization process is just a direct consequence of the shift of the value about what companies consider as their most critical asset:

- Previously, all the production process was monitored and evaluated just considering the *physical goods* which flow through the various machines.
- Now, *data* have become the most critical asset.

Experts like The Economist and Forbes recently stated that data is replacing oil as the world's most valuable resource, underling in particular the global characteristic of the phenomenon that is transforming every industry in all countries (May, 2017). It is possible to consider manufacturing digitalization as one of the different declinations of Industry 4.0. As an example, the U.S. Smart Manufacturing and the Smart Factory program, based in South Korea, aim at disrupting the market (Thoben, Wiesner and Wuest, 2017). All these initiatives have one thing in common: they heavily emphasize the use of machine tool data, framed by technologies like *Industrial Internet of Things* (IIoT), *Sensor Networks*, *Cyber-Physical Systems* and *Data Analytics* which enable their management and collection.

For the first time the dichotomy **physical product/intangible data** arises, connected to the emergence of Industry 4.0 which gave birth to a totally new perspective of how the production process should be managed. In a while it is possible to address exactly how all machines are working, their status, the production parameters and so, indirectly, to gain the total control over the product flow. Nevertheless, as all disruptions, it forces to change the as-is organization, which translates in improving both the collection and management of data, with their physical relation with production. This last requirement brought plenty of actors from all over the world to start offering solutions like platforms and software to help manufacturing companies in managing data. Anyway, the focus on certain application domains created heterogeneity in the market, making emerge a problem of excessive specificity of market solutions. In fact, focusing on niche products, vendors developed specialized analytics objectives usable only in certain branch of industry, adding complexity to the already large number of manufacturing data analytics software suites already available on the market (Lenz, Wuest and Westkämper, 2018). The main issue of such excessive specificity lies in the poor alterability and adaptability of proprietary applications beyond the original requirements. Made these premises, in the latest years a clear trend towards platforms is developing. They are becoming extensible, scalable and consistent with smart manufacturing apps, resulting more attractive to manufacturers (Ivezic *et al.*), (Chen *et al.*, 2017).

So far, we discussed about machineries and data with a general exception. Now we will go more in detail since they intrinsically exhibit certain characteristics that make them peculiar and, in some cases, difficult to manage. Lenz, Wuest and Westkämper (2018) were able to delineate their main features:

1. Focusing on the specific role that machine tools have inside a company, they occupy a key position since they are simultaneously related to different departments that have their own individual missions, which are evaluated via different KPIs, and have ultimately to achieve specific goals.

To introduce some practical examples, the stakeholders of machine tool analytics can be the quality department, the maintenance department, the operations department and the department responsible for environmental issues and energy consumption reporting (e.g., energy management or facility management) (Lenz, Wuest and Westkämper, 2018). Therefore, due to its centrality in so many different processes, it is essential to continuously keep the process under control, getting the right and valuable amount of data.

2. Among the various peculiarities of machine tool data (Lenz, Wuest and Westkämper, 2018) pointed out their *non-permanent volatile nature*: they are continuously overwritten with each cycle of the controller and have validity only at one individual snapshot of the process.

> Every specific value has associated a clearly defined physical dimension, since a key feature they must fit is the high accuracy, which is guaranteed physically by the prior calibration process. Moreover, high accuracy also encompasses the sensors that are used to capture data, translating in high reliability: the values they record are almost always plausible (correct) since the process itself could not be controlled with implausible (incorrect) measurements.

As previously introduced, machine tool data analytics must be sided by other forms of Industry 4.0 that complete and provide value to the analysis, like a unique common thread: the success of one of them is strictly linked to the development of the others. Techniques like **Internet of Things, Machine Learning** and **Deep Learning** are perfectly compatible with the manufacturing sector due to the clear interdependence between process parameters and process outcomes. In other words, the possibility to associate results with inputs prompted analytics in manufacturing to lean towards **supervised machine learning** techniques (Lenz, Wuest and Westkämper, 2018), empowered by the high ready availability of domain expertise, much more than in other domains. This last characteristic is crucial because the domain expertise is a critical prerequisite for data mining to address the complete understanding of the essential aspects of the specific field of inquiry. In other words, domain expertise is used to evaluate the inputs, guide the process, and evaluate the end products (Khairuzzaman, 2007). As a final summary, the progress in areas like deep learning and the increased availability of large data sets (*Big Data*) are making the automation process changing and first results are very promising (Ren *et al.*, 2017).

Another interesting aspect is the availability of standards in communication and data processing. Common standard are needed (Ivezic *et al.*) with the aim of providing an interface which should be able to link different systems and platforms, and should be adaptable by users and third parties to some extent (B and Hannu, 2017). An example of promising standard, which seems to meet most of the different manufacturing industries' requirements is MT Connect (Fox and Warndorf, 2008).

Come to the end of the paragraph, it is now clear that manufacturing data have become so valuable that the risk of having information exposed to non-authorized third parties, even competitors in the worst case, is now a real issue that needs to be managed carefully (Lenz, Wuest and Westkämper, 2018). Therefore, **Cybersecurity** is becoming more and more important, also because the current widely used approach, which involves each business unit being responsible for its own data collection and analysis, presents problematics about cybersecurity. It is generally preferred a more centralized approach more able to reduce the likelihood of a breech, although the incurrence of human factors and decisions do not allow to be completely safe (the most common example is the choice of administrator password), (Lenz, Wuest and Westkämper, 2018).

The following three sections of Capital Goods will try to develop all the concepts above introduced:

- The first part will be devoted to one of the most promising I4.0 technologies, related to the physical production and transformation of the product: **Additive Manufacturing** (AM). This paragraph will also be useful to create a link between capital goods sector and the aerospace industry.
- Finally, data security theme will be better developed, the main issues related to the current data management approach will be analyzed, a possible **Holistic Approach** will be provided, with the aim of providing a different structure of managing data.

Additive Manufacturing and the idea of hybrid manufacturing

Additive Manufacturing represents one of the most promising technologies in capital goods industry. In this section its main advantages and characteristics will be introduced.

Strong *et al.* (2017)'s paper will be our starting point, since it is able to enlarge the AM analysis with the concept of hybrid manufacturing, which is a really innovative process that consists in the integration of standard activities of pursuing metal manufacturing (such as machining, grinding and heat treatment) with Additive Manufacturing (AM), (Strong *et al.*, 2017). The analysis includes an investigation on the feasibility for traditional manufacturers, more in detail OEMs, to adopt hybrid manufacturing. These traditional shops are struggling to satisfy an increased demand for customized, low volume parts at competitive prices (Visnjic, 2013). Hybrid manufacturing would represent a good answer to these challenges, since it is perfectly suitable for low volume productions, with repercussions over profitability, since they are usually also more profitable. Considering more in general the major challenges that original equipment manufacturers (OEMs) are facing in this evolving supply chain, access to metal AM, process engineering time, tooling requirements, and need for quality control tools are the current problems that require to be managed rapidly. Finally, the original equipment manufacturers (OEMs) surveyed by Strong *et al.* (2017) present determined characteristics like machine availability and interest in adopting hybrid manufacturing to additionally offer post-processing services.

The choice to select additive manufacturing was taken because of its suitable applicability in capital goods sector, and because of its implementation in the hybrid manufacturing process. The last point is interesting for our research since the specific characteristic of being applicable for low production volume is perfectly compatible with the other ETO sectors taken in exam. This means that it is perhaps possible to scale and replicate it also to the other industries. Nevertheless, to finally gain this result, the first main challenge is trying to investigate if capital goods companies are willing to go through this new process implementation, resulting in a match between articles and real cases.

After this brief introduction, the following stage consists in analyzing the literature and presenting the main notions of Additive Manufacturing on a first stage, to pass then to Hybrid manufacturing. What it is important is showing that Hybrid manufacturing is no more than a direct answer to some issues that are peculiar of AM solution.

The first main benefit of **AM** regards the possibility to overcome issues such as metallurgical homogeneity in casting (Auburtin *et al.*, 2000) and machinability of super alloys (Pramanik, 2014) that are typical of traditional "bulk" shaping and material-removal manufacturing. In addition, AM can provide an unparallel advantage in design freedom through "freeform fabrication" approaches which do not require custom fixtures and jigs for every part design (Strong *et al.*, 2017). However, when compared to conventional subtractive methods such as machining, current AM methods produce parts with poorer surface finish and part accuracy (Manogharan, Wysk and Harrysson, 2015). This last characteristic should be taken into consideration depending on the application sector:

- In the case of **biomedical applications**, these aspects are not critical, but they are rather preferred to accelerate bone ingrowth (bone formation within an irregular surface of an implant) (Bartolo *et al.*, 2012).
- However, in the case of load-bearing functional parts for **mechanical** and **aerospace applications**, poorer surface finish and part accuracy require AM post-processes: they must be addressed through the *integration with the traditional manufacturing approach.* The **hybrid approach** that results is willing to combine the discrete advantages of both approaches (Manogharan *et al.*, 2015).

Outlined the general features of AM, now it is possible to go more in detail into a possible application in aerospace and mechanical applications. In these cases, part accuracies and superior surface finish are two essential requirements. Hence, there is a tremendous need to solve those challenges (i.e., increasing part accuracy, improving surface finish and material property), that we previously analyzed. According to the work of Strong *et al.* (2017), two fundamental approaches can be followed to try to address these problems: the first one focuses on the improvement of the performances of each AM process; the second one develops an hybrid approach that incorporates AM methods like it were a precursor where near net AM-made parts would be coupled with traditional processes such as machining, grinding and heat treatment. The main characteristics of these approaches are showed below:

1. The first idea is to enrich AM processes with unique processing techniques and characteristics such as energy source (laser and electron beam) and processing nature (binder jetting and material powder bed fusion).

2. The second approach would go through a hybrid approach, exploiting the flexibility of AM to produce near-net parts and then incorporating with a secondary processing to improve part accuracy, surface finish and material properties. Also other researchers like Hur *et al.* (2002) and Xiong, Zhang and Wang (2009) identified the need for secondary operations and the advantages in integrating AM and machining processes. For instance, there are also challenges. As an example, in AM activities categorized as powder bed fusion processes, in which the material is spread across each layer, such hybrid strategies would result in having limited design freedom.
3. Actually, there could be even a third approach that tries to develop a mix to fully exploit the advantages of the two approaches.

So far, we discussed about **hybrid-AM** without providing a brief definition of what it actually represents. According to Strong *et al.* (2017), it is an **integrated** set of **dissimilar manufacturing processes** such as an additive manufacturing procedures (e.g. powder-bed fusion, binder jetting, sheet lamination) linked to one or more manufacturing operations (such as machining, material property enhancement, grinding, polishing) and other non-AM manufacturing processes. Finally, to meet all required engineering specifications, all attributes of each process (i.e., part accuracy, internal grain structure) are planned concurrently.

Therefore, hybrid manufacturing can represent a very flexible innovative solution able to space across those sectors that commonly share a need of strict tolerances and accurate surface finish, even if they belong to different industries. As examples, low volume production and critical part accuracy are typical characteristics of **defense**, **aerospace**, **automotive** and **medical-industry** sectors. For instance, automobile and aerospace industries use AM for product development and highly specialized part production, whereas the medical industry uses AM for models and orthopedic implants (Wohlers, 2015). Indeed, all of them require the deployment of metal parts, whose manufacturing process is the ideal target for the implementation of additive and hybrid manufacturing systems. Instead, other materials like plastic don’t require such extensive post processing systems (Strong *et al.*, 2017).

Other actors highlighted benefits in terms of functionality and high performance, always linked to the integration of post-processing operations. These advantages are not only referred to technical considerations, but also influence the operative side of the company, which is more related to the operative production management: integrating AM can offer an opportunity to better control demand and capacity (Ford, Despeisse and Viljakainen, 2015). For instance, varying demand from multiple customers is favorable for AM service providers because of production flexibility (Nopparat *et al.*, 2013).

The development of such new manufacturing system was also supported by external factor that affected traditional manufacturing which, in latest years, is experiencing a slower growth and a stagnant market. This brought to a need to re-evaluate their use of capacity and allocation of costs to remain competitive on a global level (Strong *et al.*, 2017).

With the aim of providing a comprehensive analysis, the research will be now enriched by considerations regarding the possible consequences that the introduction of AM would have on the supply chain side (both in terms of resources and people). As all disruptions, AM can be seen at the same time as a threat and as an opportunity.

- In this regard, Manners-Bell and Lyon (2012) argued that AM would shift manufacturing facilities closer to the customer, resulting in fewer opportunities for logistics suppliers to be involved in companies' upstream supply chains. At the same time, it could represent a new opportunity for the emergence of a new sector of logistics industry, dealing with the storage and movement of the raw materials which "feed" the 3D printers, and the home delivery market of these materials would increase. In this way, AM could play the role of near-net material provider as part of an upstream supply chain, whereas distribution between support locations and maintenance locations would follow traditional manufacturing logistics.
- Looking now to the horizontal dimension of the supply chain, in certain scenarios, higher capacity utilization in AM can be achieved through collaboration among OEMs because one AM machine (or few) might have sufficient capacity to support multiple OEMs.

The last concept of the paragraph allows to expand the view also to a theme that is often been relegated to a second place when dealing with manufacturing operations: the service level. Companies are more and more understanding the importance of such aspect at the end of the production phase and new technologies like Additive Manufacturing seems to be key to go beside this direction. The following analysis will be devoted to show the "*product - service system*" (PSS) concept and how it integrates with AM. PSS is defined as a system of products, services, supporting networks and infrastructure that is designed to be competitive, able to satisfy customer needs, which have a lower environmental impact than traditional business models (Hong *et al.*, 2009). Therefore, PSS can potentially increase profit margins, delivering high quality products and remanufacturing parts of equal quality (Ford, Despeisse and Viljakainen, 2015). Through PSS, original equipment manufacturers (OEMs) will move beyond manufacturing and offer services and solutions through their products. OEMs report the need for service growth to be about 5-10 per cent a year to differentiate their products (Sommer, 2013). The underlying common principle among all the definitions is the concept of a manufacturer to expand from offering traditional products (goods) into a combination of products and services. As highlighted in a prior study, PSS has been proven to provide integrated solutions (Mont, 2007). It is possible to summarize its main advantages and disadvantages from existing literature, where it emerges the importance of PSS in manufacturing, specifically the possibility of combining traditional processes with AM methods.

- ✓ In particular, manufacturing resources and capabilities of AM to produce highly customized parts are of great interest (Cheng and Nee, 2015).
- ✓ Outsourcing of AM services was recommended by (Ford, Despeisse and Viljakainen, 2015) to gain access to AM without significant initial high investment.
- ✓ In general, it is suggested that further study on the utilization of traditional manufacturing is required to adopt AM and AM services.
- o Some of the major obstacles identified were high cost, slower speed of AM processing, added complexity for re-engineering and willingness of OEMs to re-engineer their products (Khajavi, Partanen and Holmström, 2014).

In the following section, the focus will be shifted again to machine tool Data Analytics, which, according to the literature, presents an organizational problem that must be handled before implementing any I4.0 paradigm. Data analytics is at the basis of all Industry 4.0 and, consequently, of the three technologies just analyzed (ANN, AM, Cybersecurity).

The organizational problem of Data Analytics

As discussed at the intro of capital goods sector, data and data analytics gained more and more importance with the development of Industry 4.0, since all its technologies require a real time control, and the only possibility is having a reliable digital system. Nevertheless Lenz, Wuest and Westkämper (2018) tried to demonstrate that the existing data storage system is not always reliable. Therefore, they proposed a holistic approach with the aim of helping companies in gaining complete control over machine tool data.

As-is situation

According to Lenz, Wuest and Westkämper (2018), the main issue is that machine tool data analytics processes are carried out individually, by different departments and with scarce collaboration between the groups. Each group conduces its own data acquisition and storage, curating, cleaning, processing data on their own. In this way they are highly dependent on the specific analytics objective of the individual department and it results in:

- → a significant waste of resources, time, money, doubling and tripling the work to get in the end the same outcome,
- → losing opportunities for further knowledge creation from incorporating additional features from the adjacent domains in the data analytics efforts.
- → a problem of several pockets of expertise and too many individual dedicated solutions. Hence, processes and structures tend be inefficient, exhibiting redundant processes, and making difficult the exchange between the different domains.

Technically speaking, all the individual tasks make use of the data coming from the same source, the machine tool controller and connected sensors. The machine tool controller is a Programmable Logic Controller (PLC), which was defined by Oxford Dictionary as a logic based on circuits used for automatically controlling real-time processes. The system of the PLC, in pairs with industrial PC and including graphical user interfaces, takes the name of machine tool control. It is defined as the computer control of a machine tool for a specific job by means of a special programming language (Nline, 2018). The machine tool controller can serve as the nucleus of data sources, providing structure and untapped potential when it is needed. Therefore, it is possible to think about the machine tool controller as the central instance from which all other associated services are informed.

In summary, following the reasoning of Lenz, Wuest and Westkämper (2018), this current situation is not satisfactory due to the lack of a unified analytical approach for all departments. They would require similar or even the same data for their analysis but, as the analytics are conducted independent from each other, the data are collected and stored multiple times.
To bring an example, the "design/parameter data" serves as input both for quality and the energy analytics objective, leading to redundant analysis.

Holistic Approach

As previously introduce, Lenz, Wuest and Westkämper (2018) argued that in manufacturing there is a need of moving beyond the department-objective centered approaches and more towards a data centered view, overcoming the actual machine tool data analytics process. Actually, there is an increasing number of researchers who are aware of the problem of siloed data sources: it is possible to find new architectural models (Helu, Jr and Feeney, 2017) or workflow implementation (Zhong *et al.*, 2017). The analysis of Lenz, Wuest and Westkämper (2018) aims at adding a higher-level perspective to the body of knowledge of machine tool data analytics, complementing the work and providing a guiding structure for this new field, like analogous works did (Laroche *et al.*, 2016).
Lenz, Wuest and Westkämper (2018) believe that their proposed holistic perspective could bring several advantages over the traditional, departmentalized perspective, when considering the impact on manufacturing systems as a whole. Therefore, they propose a machine tool centered perspective on data analytics, in which the machine tool controller provides the core for a transparent and dynamic structure of the various relevant data sources within the shopfloor environment.

The main difference with the previously described system of manufacturing data analytics is that data sources become the joint resource to feed all machine tool data analytics objectives. In other words, the machine tool controller serves as the single source and common path for the various analytical objectives. All machine tool relevant data repositories will be connected and accessible to a semi-centralized cross-departmental data analytics team. The joint utilization of data acquisition would lead to reduce duplications and resources. To retake the previous example, in the repository "Energy Data – Design/Parameters" data were originally collected twice, once for quality objective and again for the energy analytics, now they are collected just once, and the information is available for both of them.

SHIPBUILDING

In this chapter the influence of Industry 4.0 on *Shipbuilding* will be analyzed, with all its implications.

Intro - Environment

This sector is responsible for the transport of 90% of the international cargoes and has a key role for the functioning of the global economy, allowing import and export of raw materials and food (Balkan, 2020). From an economic viewpoint, the peculiarities of maritime trade are *high capacity*, *low profit return*, and a global scaled demand which is *regularly increasing*. Naval sector is constantly under the influence of high technological developments, in which it is required a continuous cooperation between all the actors of the supply chains (Balkan, 2020). In addition, low cost and high efficiency in maritime transport allowed the Far East countries to bring their low-cost products in the intercontinental markets, enabling them to achieve global living standards (Stuart, 2002).

Shipbuilding supply chains deal with a very complicated context due to the geographical distance of the numerous suppliers that procure material and components (Diaz, 2020), and to the deep changes in regulation that are nowadays revolutionizing the entire sector. Due to its centrality on sustainability themes, in 2013 International Maritime Organization (IMO) introduced the energy efficiency design index (EEDI), which is the regulation that defines the energy efficiency standard for the new ships (IMO 2016) (Hadjina and Matulja, 2018). Consequently, energy efficiency and eco-friendly shipping became the key criteria for the construction of a new ship (Ang, Goh and Li, 2015). This lead to a high level of customization in the contractual phase, due to the new requirements for specific structural needs, decreasing the lead time for the designers and creating high cost pressure (Wang *et al.*, 2016).

Main threats of Shipbuilding supply chains:

- Geographical distance
- High number of suppliers
- Changes in regulation
- High level of customization
- Low production and design lead time
- High-cost pressure

Therefore, shipbuilding is facing a radical transformation that involves all the actors of the chain, from the shipowners and fleet operators to the shipbuilders and suppliers. They are requested to achieve better overall performances with lower operating costs, developing more energy-efficient, reliable and environmental-friendly ships (Hadjina and Matulja, 2018). At the same time, as a matter of effectiveness, they are asked to design and build ships faster than ever before, forcing to rapidly modernize the fleet with energy efficient solutions. All this scenario leads to a totally different approach to ship design and construction, in which the synchronization between all the actors become fundamental (Hadjina and Matulja, 2018).

In this scenario, the digitalization of the supply chains, which is the main objective of I4.0, will provide *Shipbuilding* with the agility and efficiency it needs to meet all its new objectives (Ramirez-Peña *et al.*, 2020) and to be more profitable (Batista, 2019). I4.0 will affect all the stages from the design phase, to the manufacturing one, allowing an improvement in production efficiency, ship safety, cost-efficiency, energy conservation and environmental protection (Hadjina and Matulja, 2018). Both *Shipbuilding* and I4.0 intrinsically embrace the new idea of distributed manufacturing systems: with the development of globalization processes, production is no more concentrated in one site, but it is spread among different locations to finally join together for the final assembly. In addition, *Shipbuilding* has the peculiarity that the different physical locations where production is made, belong to the same manufacturing center (Ramirez-Peña *et al.*, 2020).

Most of all the biggest players in *Shipbuilding* industry understood the enormous importance of I4.0 and are preparing themselves for the changes of the next 10 to 20 years. In history, industrial revolutions always brought strong alterations in all aspects of human society and often saw governments playing a key position to enable such transition. Here, thanks to the study of (Hadjina and Matulja, 2018), a brief overview will be provided:

- Germany:

  The official "Industrie 4.0" document was originally released in 2013 by the Germany Federal Ministry for Economic Affairs and Energy. *Shipbuilding 4.0* is predicted to bring investments for the innovation of shipbuilding industry for around *12 billion Euros*, reinforcing the leading position of Germany in the international marine equipment sector, (Release, 2015). According to the "Maritime Agenda 2025", the maritime industry has an annual turnover of EUR 18 billion. In Shipbuilding 4.0 era, the *defense military budget is growing*, and German naval shipbuilding is becoming the principal industry for shipbuilding innovations.

- USA:

  American corporations founded the Industrial Internet Consortium (IIC), increasing the market size of the *Internet of Things* in shipbuilding industry. This innovation is driven by the actual situation of US shipbuilding, especially the Navy, which is facing a wave of increasing demands. The new technology had strong implementation in the US military shipbuilding, making new vessels more technological advanced, faster and better than ever before, and even with longer life cycle. At the same time, it is expected that this approach would generate 15 percent of cost savings respect to the traditional shipbuilding methods.

- China:

  The Chinese government in 2015 issued "Made in China 2025", taking inspiration from German Industry 4.0. *Shipbuilding 4.0* was highlighted as a priority in "Made in China 2025", and in the Chinese shipbuilding industry, it features the 5S: Sea, Ship, System, Smart and Services. This program aims at revolutionizing all the aspects of navigation, with implications on ship safety assessment, ship energy efficiency monitoring, maintenance, sea route, ship navigation and operational control, all connected via *Big Data*.

- Korea:

  "Manufacturing Innovation 3.0 Strategy" is the Korean version of the Industry 4.0. It took place in 2015 as part of a new change in the industrial innovation, in which it was also launched an innovation center in the shipbuilding capital of Ulsan, Busan. Three major shipbuilders were in charge of the new Ulsan innovation center: Samsung Heavy Industries, Daewoo Shipbuilding & Marine Engineering and Hyundai Heavy Industries.

What emerges from this brief analysis is that *Shipbuilding 4.0* is one of the driving sectors of Industry 4.0 in almost all the countries analyzed. In particular, there is a specific side of *Shipbuilding* that is taking a leading role in driving innovation: Navy Shipbuilding. So, having mapped in general how some countries are moving towards Shipbuilding 4.0, the next step is to understand the operational consequences that it implies. Indeed, Industry 4.0 is the main disruptive event in recent years for *Shipbuilding*: it led to a discontinuity in how the processes and resources are managed. Thus, I4.0 requires to rethink the whole maritime supply chains, to understand which structure can be more suitable for the implementation of these new technologies.

With the final aim of accomplishing such discontinuity, the next sections will be divided in the following way:

- As a starting point, the **LARG** (Lean, Agile, Resilient, and Green) paradigm will be presented. It is just one of the several categorizations of the supply chains, but according to different authors like Ramirez-Peña *et al.* (2020) and Batista (2019), it seems to be more suitable to address the sustainability theme, key for *Shipbuilding*, and all the objectives the supply chains aim to achieve in an optic of company competitiveness: rapid response to demand, flexible manufacturing, cost reduction, and inventory reduction (Carvalho, Duarte and Machado, 2011).
- While the best supply chain structure will be analyzed, the relationship with I4.0 technologies will emerge (Batista, 2019). Therefore, it will be possible to study the implementation of the **KETs** (key enabling technologies), to understand if one technology is more developed and widespread respect to the others. In this way we obtain an overall picture of the level of adaptation of *Shipbuilding* to I4.0.
- Finally, it will be possible to join the two previous analysis and so developing a model able to capture, at the same time, both the operational implications and the most interesting technologies of Industry 4.0.

LARG paradigm

In the following section, the LARG model (Batista, 2019; Ramirez-Peña *et al.*, 2020) is analyzed, identifying its paradigms and their impact/consequence on the supply chains (Carvalho, Duarte and Machado, 2011), in order to ensure sustainability and make it fully adapt to Industry 4.0 and its technologies. Due to their popularity, *Lean* and *Agile* paradigms will be analyzed at first, to finish then with the quite newer ones, *Resilient* and *Green*.

- *Lean Paradigm*

  The focus of lean approach is essentially on waste reduction for increasing competitiveness, in order to fulfil customers' needs and increase profit (Carvalho, Duarte and Machado, 2011). Among its contributions:

  - Collaborative relationship and long-lasting commitment between members.
  - Small and closer supply base with low vertical integration is preferred.
  - Involvement of suppliers from the early stages of new product design.
  - Software development with open-door policies, with assistance on suppliers' programs.
  - Frequent feedbacks which allow to share risks, benefits, and solutions.

- *Agile Paradigm*

  The supply chain objective here is to deliver the right product, in the right quantity, in the right condition, to the right place, at the right time. Since customers' needs are continuously changing, supply chains must be able to adapt to future swapping and appropriately meet market requirements (Carvalho, Duarte and Machado, 2011). Through the integration of different partners, it is possible to acquire new skills which allow to respond quickly to the changes in the environment (Baramichai, Zimmers and Marangos, 2007).

Authors commonly agree that the supply chains should be *Lean* for large volume productions with low variety, in stable, predictable, and controllable business environments. Whereas *Agile* paradigm is required for small volume with high variety and unpredictable market changes.

Nevertheless, Gosling and Naim (2009) highlighted that there are more broad disagreements related to boundaries, definitions and applicability of leanness and agility in many different sectors and although both lean and agile strategies were proposed as strategies for the ETO sector, there is no clear answer regarding their applicability.

Other authors like (Ben Naylor, Naim and Berry, 1999) introduced the term “Leagile” for the supply chains whenever demand is variable and there is a wide variety of products.

- *Resilient Paradigm*

  Crises of various causes can shake the previously established path of a firm. Therefore, resilience can be defined as the ability to overcome the disturbances and recover the state the company was, before encountering the interference, (Ramirez-Peña *et al.*, 2020). Furthermore, resilience is considered as the capacity to adapt and continuously adjust the supply chain to events that threaten the balance of activities (Dg *et al.*, 2017). The main result of choosing resilient paradigm is the shift of the focus from the classical minimization of costs to strategic decisions more oriented to cope with unexpected alterations, in optic of avoidance of the undesirable state, (Carvalho, Duarte and Machado, 2011).

  Some example of resilience is designing strategies to restore the previous state of the system, or changing the level of effectiveness of the potential warning (Dg *et al.*, 2017). It is now possible to highlight the two main threats of adopting this paradigm:

  - Need of a total visibility of the supply chains, which is in some cases very difficult to achieve. This characteristic is shared with the Agile paradigm and with Industry 4.0 (Christopher and Peck, 2004).
  - Several authors like (Mensah and Merkuryev, 2014) consider this paradigm very costly and complicated to implement. Therefore, they recommend *Lean Production* and *Six Sigma* as alternatives, since they provide flexibility and a corporate culture that can indirectly lead to a resilient supply chains.

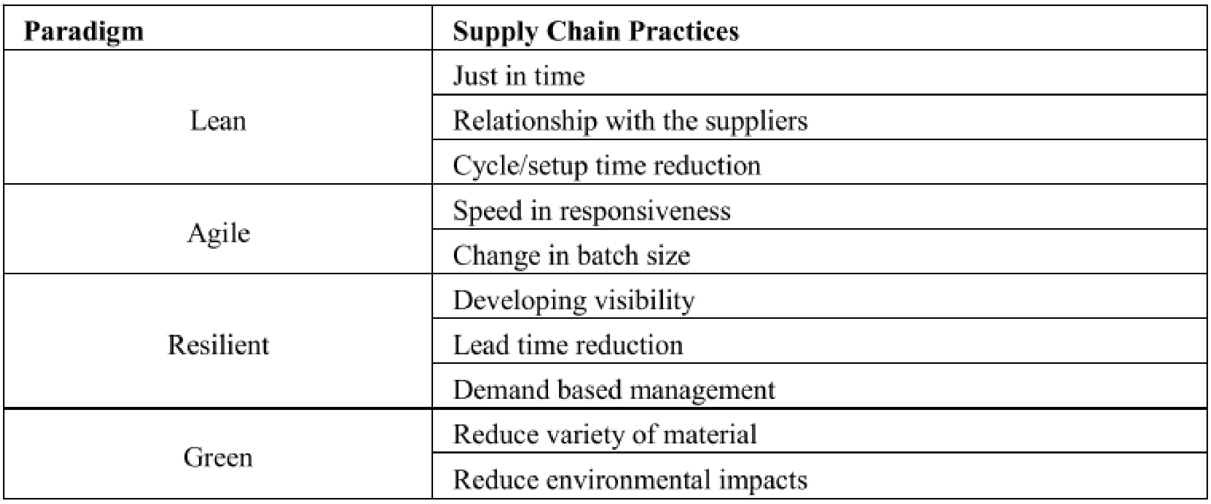
- *Green Paradigm*

  It is the most recent paradigm, raised in the latest years due to the increasing customers’ willingness to understand how firms manage the entire operations of their supply chains, both in terms of social and environmental rights. It is useful to provide some different definitions:

  - Green supply chains could be defined as "Integration of the environmental dimension in the supply chain, including product design, procurement and material selection, manufacturing process, product delivery to final consumers and end-of-life management" (Srivastava, 2007).

- Sustainable Supply Chains regard the voluntary integration of economic, environmental, and social considerations within supply chain management from the stages of product design, to the manufacturing process itself, until the delivery to the final consumer and even to the end-of-life management of the manufactured product (Srivastava, 2007).
- Closed-loop supply chains "include the return processes that the manufacturer has to deal with the intent of capturing additional value and further integrating all supply chain activities"(Guide, Harrison and van Wassenhove, 2006).

In order to make an easier comparison between the main differences of the 4 paradigms, Figure 6 help in summarizing all the different practices:



Paradigm	**Supply Chain Practices**
Lean	Just in time
	Relationship with the suppliers
	Cycle/setup time reduction
Agile	Speed in responsiveness
	Change in batch size
Resilient	Developing visibility
	Lead time reduction
	Demand based management
Green	Reduce variety of material
	Reduce environmental impacts

Figure 6. LARG paradigm main practices (Azfar, Khan and Gabriel, 2014).

Once provided a general explanation of the LARG model, it is now possible to bend it to our case, finding which of these *paradigms* are more *suitable to bring Shipbuilding into the world of I4.0*. First of all we have to make a consideration: the work of Ramirez-Peña *et al.* (2020) and Batista (2019) is quite new since there is no previous experience about quantifying the contribution of the LARG paradigm in the shipbuilding industry. In the literature it is possible to find an analogous example only in the experience of Azevedo, who studied its implications in the automotive sector (Azevedo, Carvalho and Cruz-Machado, 2016). The aim of Ramirez-Peña *et al.* (2020) and Batista (2019) was trying to evaluate shipyard in the process of adaptation to *Industry 4.0*, focusing on all supply chain implications. Chronologically, the study of Ramirez-Peña *et al.* (2020) came earlier developing a conceptual model that separately confronts the different paradigms of LARG and confronts them with the enabling technologies of *Industry 4.0*. What (Batista, 2019) was able to add to the previous work was a deeper analysis of the KETs (Key enabling technologies), coming up with a possible preferred technology to implement to this specific sector.

Ramirez-Peña *et al.* (2020) started the analysis from the **five milestones** of the performance model of Industry 4.0 (Energy, Environmental, Economic, Functional and Social), with the idea that the best LARG paradigms should be those able to address all the milestones, or at least the majority of them. The conclusion was that ***Lean*** and ***Green*** were the only paradigms able to address such milestones, improving the overall performance of the supply chains from the point of view of *Industry 4.0*. In addition, both paradigms embrace the social aspects, which are new in the field of I4.0. Also other authors (Arjestan and Rahimi, 2017), highlighted a relationship between Lean, sustainable supply chains and social aspects. The *Resilient* paradigm, instead, seemed to fulfil only the Social and Functional aspects, while the *Agile* paradigm fulfils mostly the economic one. Both *Resilient* and *Agile* are important for the supply chains, but according to the authors they are overcome by the *Lean*, which we just saw that can intrinsically cover the Resilient part. In addition, the I4.0 must take precedence over the market needs; hence, it ceases to be a requirement and make sustainability themes (Green) over economical (Agile).

		I4.0 Perfomance Aspects				
		Economic	Energy	Enviromental	Functional	Social
Supply Chain Paradigms	*Lean*	o	o	o	o	o
	Agile	o			o	o
	Resilient				o	o
	Green	o	o	o	o	o

Figure 7. LARG paradigm main practices (Ramirez-Peña *et al.*, 2020)

Instead, Batista (2019) started the analysis with a Delphi study, which is a technique that allows to gather information through a consultation with expert. They included both personnel from the shipbuilding sector itself and academics directly related to the sector. They were asked to provide a classification of LARG paradigms according to their importance for shipbuilding, and, in the same way, an analysis more related to their level of implementation (i.e., how much each of the studied paradigms is implemented). The result was partially in contrast to (Ramirez-Peña *et al.*, 2020): the *Lean* paradigm is again the most valued one, but here it was closely followed by *Agile*, even more than *Green*, despite its fundamental importance for this sector. Regarding the implementation level, it was observed that *Lean* and *Green* were the two most implemented paradigms, leaving behind the *Agile* and *Resilient*, a result that is in line with the previous study.

Finally, Batista (2019) provided also an evaluation of the level of LARG model in Shipbuilding, highlighting that, according to the consulted experts, its implementation is on the way but still requires other efforts, mainly because all its benefits have not been achieved yet (Azevedo, Carvalho and Cruz-Machado, 2016).

Consequently, Ramirez-Peña *et al.* (2020) and Batista (2019) came up with results that quite coincide, despite the usage of totally different procedures: ***Lean*** and ***Green*** seemed to be the most suitable paradigms for the supply chains to implement Industry 4.0. This shows that apparently in *Shipbuilding* industry it is preferred going for long relationship with suppliers, with the benefits that this entails, and aim at satisfying the certifications and the corresponding regulations to reduce energy consumption (Batista, 2019), knowing that Green paradigm is considered as a key factor in *Shipbuilding* to increase competitiveness of the company (Mello and Strandhagen, 2011) and to improve the energy efficiency (Xie, Yue and Wang, 2017).

Continuing with the analysis of the results, it is reasonable that *Resilient* is a paradigm considered difficult to get into practice because of the high associated cost (Batista, 2019). The preference of Lean over Agile is instead quite an unexpected result. They are the two most famous and studied paradigms and are often put in contrast against each other. According to the articles just mentioned, there could be several reasons at the basis of the success of *Lean*. It has always been the most widespread and used paradigm for the longest time (Batista, 2019), while *Agile* paradigm does not seem to be entirely in line with the sector in terms of volume and the great variety of production required (Ben Naylor, Naim and Berry, 1999). What it is peculiar of this consideration is that *Shipbuilding*, as the majority of the ETO sectors, is usually considered by researchers as a sector that suffers from tremendous complexity. This complexity derives, among the other factors, by the uncertainty that is faced at all the levels of the supply chain:

- All the products are unique and do not necessarily contain the same raw materials.
- In addition, the end-user is prepared to accept long lead times and the demand for products is highly variable.
- Nothing can be managed by forecasting, since the level of customization of each single order is so high that it is even impossible to held a stock of raw materials, since it would run the risk of them to become obsolete (Wong, Wong and Boon-itt, 2018). Hence, if a particular

product failed entering the marketplace, then this supply chain would not have any exposure to the costs of overstocking.

These results are very interesting for our research, since they can represent a basis for possible interviews to various firms, to understand:

1. if they are implementing management choices to exploit the benefit of LARG paradigm,
2. If they are going closer to a paradigm (rather than another),
3. if these choices are helping the company to embrace I4.0,
4. to finally understand if the results obtained by the literature (*Lean*, *Green*) get a match with a real situation, or if the firm prefers adopting other strategies.

Technologies:

After having concluded the analysis regarding the LARG paradigms, the focus now passes towards Industry 4.0 and all the twelve key enabling technologies (KETs) that characterize it: *Additive Manufacturing, Big Data, Cloud Computing, Augmented Reality, Autonomous Robots, Automatic Guided Vehicles, Blockchain, Cybersecurity, Horizontal and Vertical Integration System, Artificial Intelligence, Internet of things* and *Simulation* (Ramirez-Peña *et al.*, 2020). Before studying them, it is valuable to map a comprehensive picture of the main challenges in the application of such technologies to *Shipbuilding* and *Shipyards* (Eide, Norske and Isaksen, 2008):

- IT security problems: in case of large data concepts, they regard the possibility of accessing all kind of personal and machine data. To overcome this, robust internet security protocols and procedures must be developed.
- From design phase to production, from material suppliers to subcontractors and regulatory authorities, *Shipbuilding* requires many organizations to work together and exchange data. This is a great advantage but increase dramatically complexity.
- Trained staff deficit.
- Probable resistance of the sector stakeholders to Industry 4.0.

The I4.0 technologies must start from these considerations to improve *Shipbuilding* in its whole, to enable interconnectivity among all the different stakeholders, which are linked by invisible ties that allow a complete and immediate data transferring. Cyber-Physical System of the Maritime 4.0 enable overall connectivity and data exchanging between the onboard private clouds of ships and helicopters, the onboard private cloud of ports and the overall public community cloud.

But how it is possible to create such a complex structure? The key word highlighted by Balkan (2020) is automation, which has been greatly increased in ships, shipyards and ports. Basically, it enables the growth of production speed and efficiency, reducing costs and use of manpower. Anyway, automation in *Shipbuilding* was possible only after a certain technological investment, with the result of a parallel development in the field of computer and electronics (Policy, Erikstad and Fagerholt, 2012). Indeed, the computer support was inevitable in the management of operating systems and of the machines used in the enterprise. Digitalization is essential for providing this support easily and inexpensively. Digitalization is the transfer to a digital environment of data or operational processes that were previously created manually. Moreover, the power of computers made the processes faster, and data access and resource management more simplified (Balkan, 2020). As a result, the widespread use of the Internet made also possible the emerging of a revolutionizing technology: Internet of things. This new approach can be described as a wide network of communication in which physical objects are interconnected with each other: the purpose is to connect objects to other objects and people. In *Shipbuilding*, characterized by wide geography and 24 hours a day operations, the benefit of IoT can be enormous (Eide, Norske and Isaksen, 2008).

The concept of digitalization was also developed by Raman *et al.* (2018), who identified in *Big Data* a key factor able to add value to the company, enhancing cost saving (efficiency) and increasing customer satisfaction (effectiveness). In fact, digitalization enables availability, with the possibility to exchange and process real-time data and information in the *Shipbuilding* process. Nevertheless, it is essential to side *Big Data* with standards, norms, clear guidelines that allow to manage such a huge amount of information. Therefore, a standardized, unified, and coordinated infrastructure made by shipbuilders and suppliers is required for the design, production, and maintenance of the ship. A lack of real-time collaboration or a discontinuity in the data flow would negatively affect the speed of construction and the overall costs, resulting in a loss of profit. To avoid these consequences, it is necessary to introduce powerful algorithms of Machine Learning able to assert from the huge mass of data the actual useful information to predict the future and to make them understandable to human operators (Ang, Goh and Li, 2016). Summarizing, the digitization of the design and ship construction can build the pillars for the overall digitization, although it requires a further development of:

- Process optimization
- Standardization
- Digital interconnectivity
- Optimization of information flow
- Interfacing of the material and information management within the entire supply chain

Now it will be provided an example of the potentiality of Big Data in Shipbuilding: Product Lifecycle Management. Ship construction requires an integrated planning of many processes from the procurement of equipment and materials to the design activities, even subcontracting to class and legal organization activities. This integration can be achieved through Product Lifecycle Management (PLM), which is a data management system able to integrate data, process, business systems and ultimately people (Balkan, 2020). PLM software enables efficient and cost-effective monitoring and management of this data throughout its life cycle, from the product idea to its design, production, service life and ultimately discard. The IT integration, in addition, can increase machine automation in production, especially in activities related to automated jobs, with the result of allowing independent decisions and reducing the error rate (Balkan, 2020). An example of application regards the ship design phase: it is possible to produce a ship prototype quickly by iteration and by design optimization of order parameters from the existing ship database. In the same way PLM structure can simplify the shipment of design documents to the shipyard (Lezzi, Lazoi and Corallo, 2018).

So far it was discussed the key role of digitalization in *Shipbuilding*, now become like a pre-requisite, and two of its most important implications: Internet of things and Big data. The following analysis will focus on other technologies to understand their level of implementation. The main idea that emerges from the literature is a lack of an already established technology that arises among the others. Batista (2019) evaluated, in relation with the KETs, the overall readiness of the sector to the implementation of Industry 4.0, always relying on the Delphi method. While the previous study for the LARG analysis was indicating the level of implementation of the paradigms of the supply chains, now it indicates the level of importance of each KET to each paradigm. The result suggests that *Shipbuilding* is committed to adapt to Industry 4.0 but, because of the values obtained, it is not clear which technology can be more interesting to be implemented sooner.

Ramirez-Peña *et al.* (2020) developed an index defined as the percentage represented by the relationship between the number of documents studied, and the average number of citations in these documents, trying to provide a hierarchy of technologies. The technology with the greatest weight resulted to be Additive Manufacturing, also the one that has been mostly implemented so far. As followers, they found the *Vertical and Horizontal integration systems, Cybersecurity, Big Data (*previously discussed)*, Artificial Intelligence* and *Blockchain.* At the end, *Internet of Things, Cloud Computing* and *Robotics,* leaving *Augmented Reality* and *Automatic V*ehicles in the lowest position. This helps to give an idea of which of the enabling technologies will position Shipbuilding in Industry 4.0, representing even a chance for the whole working world to improve and modify job definition and working processes.

- ***AM*** is one of the most disruptive technologies in the context of Industry 4.0 and its main advantage is the reduction of the number of suppliers (Berman, Zarb and Hall, 2012), which brings to a reduction of complexity in the management of the process, reduction of costs and possibility to have the piece you need just-in-time, in the specific place and quantity. (Muthukumarasamy *et al.*, 2018) identifies *Additive Manufacturing* as a fast-growing technique and advises its incorporation into the supply chains in an optic of making processes more sustainable.

- ***Cybersecurity*** is useful in complex supply chains like *Shipbuilding*, where many actors and external suppliers are involved, since it allows achieving visibility along the supply chains (Larry and Usaf, no date). Nowadays, data has become the most important resource for a company, replacing the physical product. Nevertheless, it is much easier to get improperly access to data, and even hack them, so the issue is how to be sure that a key information remains secure. *Cybersecurity* establishes basic requirements in contracts, assessing and mitigating security risks. Through mapping the key suppliers at all levels, including possible backup supply sources, it is possible to prevent and manage events of interruption due to poor quality or counterfeiting (Ramirez-Peña *et al.*, 2020).

- ***Blockchain***, strictly following in the hierarchy of Ramirez-Peña *et al.* (2020) and closely linked to *Cybersecurity*, it is able to generate highly automated, self-executable and functional transportation systems, ensuring at the same time an eco-friendlier method of distribution. A blockchain enabler within the shipping can create multiple contracts in numerous blockchain systems connected to a single chain, so it is able to improve them with restrictive energetic information not shared inside the blockchain network (Balkan, 2020).

Concluded the overall picture of the most interesting technologies according to Ramirez-Peña *et al.* (2020)'s analysis, now the following step is the creation of a model to understand how the selected enabling technologies boost the LARG paradigm, which means: **understanding the relationship between the traditional supply chain paradigms and Industry 4.0.** Ramirez-Peña *et al.* (2020) defined a conceptual model that can be applied to various case studies. First, they suggested that it is necessary to specify exactly the part of the shipbuilding where the model will be applied. It is possible to distinguish three major areas: Block Assembly, Painting and Hull Erection. Then, there is the choice of the paradigm. As we saw in the previous stage, *Lean* and *Green* paradigms are the ones that most positively affect the performance of *Shipbuilding*. They are mainly linked to the Environmental, Economic and Energy aspects and are associated to six of the enabling technologies:

Autonomous Robots, Autonomous Vehicles, Additive Manufacturing, Cybersecurity, Cloud Computing and *Augmented Reality*. The meaning is that these technologies, once related to a supply chain which is Lean or Green, will provide the most effective global performance. Then, the remaining Functional and Social aspects of the performance model are included. In this way, Resilient and Agile paradigms reinforce Supply Chains through the implementation of the six remaining enabling technologies. *Horizontal and Vertical Integration, Big Data, Blockchain, Simulation, Internet of Things* and *Artificial Intelligence*.

Then, we concluded the reasoning introducing the ***final model***, which was able to compare the technologies with the previous analysis of LARG paradigm. The aim in this case was to understand how a company should behave to fully exploit the potential of I4.0 and how should prepare its organizational structure of the supply chain. In particular, according to the model of Ramirez-Peña *et al.* (2020), if a *Shipbuilding* company wants to improve its performance in the I4.0 context, it must adapt in two different stages its supply chain:

1. A first phase focused on Sustainable, Economic, Energy, and Environmental performance, which sees the implementation of ***Lean*** and ***Green*** paradigms, the ones with greatest influence on the overall profitability of the company

and

2. a second phase that defines the Functional and Social performance aspects, targeting ***Agility*** and ***Resilient***, positioning the sector on the road to Shipbuilding I4.0.

Such an analysis indirectly implies the implementation of the enabling technologies again in two phases:

1. A first phase would lead to a sustainable shipbuilding supply chain through the implementation of the following technologies: *Autonomous Robots*, *Additive Manufacturing*, *Cloud Computing*, *Autonomous Robots*, *Cybersecurity* and *Augmented Reality*.
2. A second phase where the Functional and Social aspects converge through the implementation of *Horizontal & Vertical Integration*, *Big Data*, *Blockchain*, *Simulation*, *Internet of Things* and *Artificial Intelligence*, reinforcing the Resilient and Agile paradigms.

In this way, it is achieved total visibility and connectivity required on the Shipbuilding 4.0 supply chains. The main limit of this model is the lack of previous implementations, so it is not possible to predict how it should behave in a real context.

Finally, a deep focus on other two remaining technologies was provided. They have a peculiarity; their application so far has been quite "turbulent" due to the concern of people to implement them. In some cases ethical (problem of 5G), in other more a matter of lack of trust in technology itself (autonomous vehicles). Actually, they could bring important benefits. They could enter in very specific tasks that would require really complex activities to be performed in terms of resources implemented and security, like rescue of stuck vessels.

The last part of the paragraph will be dedicated to other two technologies: **5G** and **autonomous ships**. An interesting study was made by Balkan (2020), in which autonomous ships are considered as a solution to different issues that affect the shipbuilding sector. Therefore, there will be a summary of the problems and then an explanation of the technologies.

According to (Balkan, 2020), one of the most troublesome issues the maritime sector has to face is **conjunctural problems**. These problems can be macroeconomic changes (such as economic crises and political crises) which cannot be prevented by any direct action. The only possible intervention is to reduce risk damages through the adoption of risk management plans. Nevertheless, such plans are difficult to be standardized and are not always valuable in different situations. Indeed, they have to be reshaped as necessary, and this shaping covers the following areas (Dalsøren *et al.*, 2009):

1. *Management area:* management will react differently to various situations
2. *Organization area:* flexible renewal of the organization to respond to different situations
3. *Competence area:* personnel is competent and trained to respond to different situations
4. *Digital area:* digitalization enables the collection, storage and use of large and diverse information

Given these areas of importance, companies operating in the maritime area can adopt the following responds (Policy, Erikstad and Fagerholt, 2012):

1. Shaping the top management according to strategic management concept
2. Financial, budgeting, organizational structure required for crisis management

3. Maritime organizations; marina, port operation, shipyard business and other areas of activity, such as logistics
4. Development of Management Information Systems, transition to digital trade, and automation with high reliability

Balkan (2020) identified the new 5G technologies and blockchain (previously discussed) systems as the specific applications able to completely reshape maritime sector in all aspects just highlighted, with an additional benefit in terms of security. As an example, 5G is expected to facilitate the introduction of smart drones able to monitor the ship leaving and entering from ports, improving communication for ship traffic. 5G can be combined with other I4.0 technologies like Internet of Things and Autonomous Shipping:

- It can be combined with *Internet of Things* sensors that can assist providing real time information and accurate positioning in the rescue of stuck vessels.
- It can be used with *Autonomous shipping*, although it is a quite peculiar case since it is not a technology totally trusted by users. Nevertheless, in the shipbuilding industry, autonomous shipping could instead potentially save lives, thinking for example at the safety problem of recovering vessels, that most of the times contribute to adding harmful rubbish in the seas.

Therefore, although the development of autonomous ships is still at the experimental stage, the implementation of 5G technologies in the field of autonomous shipping would provide a stronger base for remote-controlled ships, remote-piloted ships and vessels powered by artificial intelligence.

To conclude the study of *Shipbuilding*, it is interesting to group some of different considerations about future implementations (Balkan, 2020):

- Marine-related organizations should be reshaped to meet the future focus on the construction of environmental-friendly ships and green harbors and shipyards.
  The modification of ships in accordance with the new measures and regulations related to the increasing environmental protection sensitivity is a very difficult and expensive task.
- Automation, Digitization and Internet of Things are inevitable for the management and operation of growing maritime organizations. Furthermore, information mining and artificial intelligence applications will be unavoidable especially in large companies during the planning and execution phase.

- Increasing traffic density in the seas of the world requires more comprehensive measures for navigation safety. There is a need for more excellent navigational aids that are easy to use and make it easier for users to make decisions.
- The most critical issue during the establishment phase of large-scale companies is financing. Therefore, strategic planning should also be focused on financing. Furthermore, public relations and law, which were not given much importance before, should be given importance.
- Advanced technologies are constantly affecting maritime trade and the reaction time is very short. They must be managed by manpower, who must learn how to use these advanced systems. In order to create high quality manpower to be employed in maritime trade, the training system needs to be arranged in a dynamic way to meet the needs.

DISCUSSION

The last session will provide considerations based on the previous analysis, trying to unique all information and give to the reader a quite clearer overall picture of Industry 4.0 applied in Engineer-to-order supply chains, from an operational and technological point of view.

This analysis started trying to combine the domains of ETO supply chains and Industry 4.0 technologies. Dividing the research per sectors, it came out that all of them found a similar breeding ground on which sowing the seeds of the fourth industrial revolution. Indeed, they had to face similar issues, reflecting from one hand the uncertainty of demand side, from the other the uncertainty of supply side. In the middle, the answer is the adoption of the new I4.0 technologies. Nevertheless, a mere unrestricted embracement of the technologies is not valuable at all: it must be coherent with the internal organization of the supply chain. This last point became clear addressing in Shipbuilding the LARG (Lean, Agile, Resilient, Green) framework, translating in a very interesting idea also for an application in the remaining two sectors.

Therefore, the two main topics that were highlighted from the literature review can be addressed:

- A first consideration that involves the management side, regarding some possible ways the ETO supply chains can organize themselves to answer to such a turbulent environment: LARG analysis. Looking at the different paradigms, some of them are old (Lean, Agile), some other quite new (Green, Resilient), which indirectly reflects, in the latest years, a change in the needs and the requirements people are focusing on.
- A second consideration that regards the actual level of implementation of Industry 4.0, and how the new technologies seem to be prompt helping companies.

All of this is preceded by an environmental analysis whose main objective was to understand if all these different industries faced similar issues and constraints. Thus, discovering interesting insights in a sector could also become useful for the others, spreading cross-sectorial considerations.

First of all, the topic analyzed is not merely economical and not only relates to private companies, but, in many cases, it regards also public authorities. Since we are dealing with a real revolution, all the analysis of the sectors sees the governments playing a key role in developing such new technologies. In this regard, states can mitigate some of the most diffused challenges, which are the exorbitant costs of implementation and the difficulties in understanding changes in regulations (an aspect threated in Shipbuilding sector). Thinking for example at the case of Naval Shipbuilding, here the most important innovations are being pushed by the different governments which have interest in developing a strong and technological Navy for political reasons.

Moreover, it is now useful to put in comparison as example the Aerospace and Shipbuilding sector, to address if they share similar challenges, remembering the most critical threats introduced in the previous chapter:

AEROSPACE (Spare parts)

- the increase in competition in worldwide air traffic,

- the growth of high quality and safety standards,

- low lead time,

- high-cost impact for low valuable spare parts

- geographical position of suppliers,

- long-lasting relations with suppliers.

SHIPBUILDING

- geographical distance,

- high number of suppliers,

- changes in regulation,

- high level of customization,

- low production and design lead time,

- long-lasting relations with suppliers,

- high-cost pressure.

Simply putting the points side by side, it becomes clear how they are full of similarities that reflect the uncertainty at downstream and upstream part of the supply chain, from clients to suppliers.

Made all these premises it is not easy to answer about the actual implementation level of Industry 4.0 in ETO supply chains, since there is not one common answer to all the sectors. It is not something homogeneous, it is still linked to the individual decision of the single company. Anyway, it is possible to represent some of the barriers that are quite common for all the sectors analyzed:

- Costs,
- Lack of knowledge and competence,
- Fear of the transformation (cultural and emotional).

To better explain the first cost voice, we can think about the technology that was mostly discussed in this thesis, Additive Manufacturing. According to almost all the researchers, its strongest executing barrier consists in the huge cost of implementation: if companies have to invest such a huge amount of money without being able to predict the possible future benefits, for them it is difficult to invest.

About the second point, in all the industries a common problem of trained staff deficit was identified, and the only way to solve it would be largely increasing personnel training cost (see point one). It is the case of the two last technologies seen in Chapter 3: 5G and autonomous ships.

Finally, about the cultural sphere, the example of Additive Manufacturing is quite significant. AM is able to completely revolutionize the old role of suppliers. According to the implementation strategies discovered (centralized, decentralized), they would be forced to completely change their internal operational structure, their way of working, but also their geographical location, since AM would require them to enclose to the customer manufacturing facilities. Therefore, it is really difficult to convince all the actors involved that this solution would bring benefits to all the supply chain players.

Just to provide some examples about existing implementations in real life:

- Additive Manufacturing is already being implemented in sectors like Aerospace, but also in others like the automotive ones. This is a very relevant factor because we are dealing with two sectors that are almost at the opposite side of the supply chain structures identified in **Figure 1**, exactly at the Introduction chapter. The decoupling point of automotive is almost at the end of the production phase, really close to the customer side. To support this evidence, in aircraft and automotive industries, AM already managed to produce low-weight components, providing also higher safety standards and improving the overall aircraft SC dynamics. We saw that Boeing recently used selective laser sintering technology to produce thermoplastic spare parts for its commercial 737, 747 and 777 aircrafts.
- A possible example of Shipbuilding instead is represented by the outcomes of the Shipyard 4.0 implementation, resulted from the cooperation between University of Coruña (UDC) and Navantia Spain Navy shipyard (Hadjina and Matulja, 2018). In this case such collaboration enabled an improvement of smarter energy consumption, efficient pipe logistic and shipyard production, usability of the shipyard facilities and real-time yield optimization, [16]. The

technology considered in this case was among those not examined in our analysis, the radio frequency identification (RFID): it allows traceability of the pipes used in the ship construction in the shipyard. Some of the largest European shipyards from Italy, Spain, Germany, Finland started with the implementation of the Shipyard 4.0 concept. Implementation concept is different in every shipyard according to the present technological level and financial the possibility of the investment in the research and development in this concept (Hadjina and Matulja, 2018).

Anyway, it is necessary to add that they are some few isolated cases documented in the literature.

Technologies

Concerning the technologies and how they can solve the main issues of ETO supply chains, still there is high uncertainty. For some of them like AM, boundaries are clearer, for others like Blockchain, they are fuzzier.

What is certain basing on all the researchers taken into consideration is that *digitalization* (sided by the most famous *Big Data* concept) phenomenon has become fundamental for all the companies. In chapter 3 it was explain how data is becoming an increasingly valuable resource, till competing with oil. At the same time, manufacturing is experiencing the digitalization process, till transforming towards a smart manufacturing system.

We saw it in maritime sector, but we can bring it also to the others, just thinking at the holistic approach studied in machinery sector. Starting from Shipbuilding, researchers identified in *Big Data* a key factor able to add value to the company, enhancing cost saving (efficiency) and increasing customer satisfaction (effectiveness). The real disruption is the possibility to exchange and process real-time data and information in the *Shipbuilding* process.

- ➔ The final aim is to create a standardized and unique infrastructure whose nodes are in that case the shipbuilders and suppliers. Now, it is possible to extend this concept also to Aircraft builders and machine tool companies, till arriving to a generic ETO infrastructure node.

It was possible to make these connections since it was previously shown that these sectors share important similarities. The first connection will be made with *Aerospace* and its peculiar spare parts supply chain management. In this specific case the network generated by *digitalization* would have strong consequences starting from the design and production phase, and even to the maintenance of the aircrafts. In addition, it perfectly enters in the optic of AM implementation:

- thinking for example to the CENTRALIZED implementation way, the eventual synergies generated with the connection among the company and the suppliers would become really valuable if in real time it would be possible to be aware of all information of variation of demand from one side, and of availability of suppliers from the other.

Here enters also the last sector: Machinery, thanks to its holistic approach. Remembering the definition given in Chapter 2, this approach had the final aim to achieve synergies, reduce redundancies, and create new cross-domain knowledge and it was proposed as a machine tool data analytics approach. It is useful to recall it, since it can be the basis on which build all the other technological tools. Such approach represents a way for structuring data not only from a technological viewpoint, but also from an organizational one, trying to optimize the internal flow of information, not only in the company domain, but also within the entire supply chain. Recollecting the main characteristics that make perfectly suitable to apply the holistic approach in a cross-sectorial application:

- It allows eliminating inefficiencies and improving the overall use of resources as well as data quality;
- it requires a dedicated and cross-departmental data analytics team in which there are both expertise in data analytics and in manufacturing, in order to have the complete knowledge of the process both from a physical and from a virtual viewpoint;
- as a combination of the previous point, it allows to decrease uncertainty both on demand and supply side, providing a broader understanding of internal and external factors, till preparing companies for the uncertainty and new demands the future will bring.

Finally, a last recalling of the concept of *Machine Learning*, essential in this case to process the huge amount of information collected, asserting the actual useful information to predict events in the future.

Summarizing, the digitization of the design and ship construction can build the pillars for the overall digitization, although it requires a further development of:

Ending the reasoning looking at the main drawback, the proposed holistic approach faces several challenges and barriers covering both technical and organizational aspects, as depicted before.

The only way it is possible to such radically transform these industries through digitalization is to apply the principles of Industry 4.0, understanding that it is not a quick process and it is not possible to have an immediate complete application. The only way is to proceed gradually and decide to allocate investments on the internet infrastructure and data processing units as the most important part of production instead of being seen as support for production.

AM

Additive manufacturing was the only technology discussed in all the sectors taken into consideration. Above all, we discussed its application in spare parts supply chain and in hybrid manufacturing of Machinery sector. Before they were studied separately in Chapter 2.1 and 2.2. Now we will try to include them in a unique reasoning.

An important part of the discussion is dedicated to Additive Manufacturing. In Chapter 3 its application was discussed in particular for spare parts management (Aerospace) and as enabler of hybrid manufacturing (Machinery).

On the light of all the analysis performed in the previous chapter, this technology seems to be the most compatible with ETO industry, due to technological and operational characteristics. Here they are briefly recollected:

1. First of all, Additive Manufacturing is perfectly suitable for low volume production industries, which is the key characteristic of Engineer to order supply chains.

2. It allows to produce near-net parts. Such property is useful in combination with a secondary traditional industrial technology able to improve part accuracy, surface finish and material properties. In this way it is possible to use the flexibility of AM for the initial stage, reducing lead time and improving the overall process performance. This is very relevant for sectors like Aerospace, in which poor surface finish is a very critical issue.

3. In addition, it can be implemented in reverse. In fact, AM can be used for post processing services. It is strictly linked to hybrid manufacturing from an operational viewpoint. favorable for AM service providers because of production flexibility.

4. As consequence to the previous points, AM can perfectly coexist with traditional technologies and it is a perfect combination between existing technologies and new ones, also in optic of cost reduction. As the major drawback of AM are the too high costs. This also means that companies can go through a gradual introduction of this technology, decreasing the initial investment.

5. Another property is the Design flexibility, which allows a weight reduction up to 80%, and fewer materials usage. Therefore, AM is considered a *"lean"* approach (Togwe, Eveleigh and Tanju, 2019). These parts will maintain the same functionalities. Briefly recalling the operational implications of *lightweighting*, it includes fewer material usage in relation to traditional manufactured designs, making AM a **"lean"** approach (Togwe, Eveleigh and Tanju, 2019). Such approaches are gaining more and more popularity in Aerospace industry, due to the operational simplicity and the clear financial savings, sided by reducing waste processes. In particular, AM is a near net shape process, therefore it can enable raw material cost savings over traditional parts (Dehoff *et al.*, 2013).

6. In this regard, Manners-Bell and Lyon (2012) argued that AM would shift manufacturing facilities closer to the customer, resulting in fewer opportunities for logistics suppliers to be involved in companies' upstream supply chains. At the same time, it could represent a new opportunity for the emergence of a new sector of logistics industry, dealing with the storage and movement of the raw materials which "feed" the 3D printers, and the home delivery market of these materials would increase. In this way, AM could play the role of near-net material provider as part of an upstream supply chain, whereas distribution between support locations and maintenance locations would follow traditional manufacturing logistics.

OTHER TECHNOLOGIES

Finally, a deep focus on other two remaining technologies was provided. They have a peculiarity; their application so far has been quite “turbulent” due to the concern of people to implement them. In some cases, ethical (problem of 5G), in other more a matter of lack of trust in technology itself (autonomous vehicles). Actually, they could bring important benefits. They could enter in very specific tasks that would require really complex activities to be performed in terms of resources implemented and security, like rescue of stuck vessels.

In addition, it is necessary to create an infrastructure that will ensure the management of all processes, from the idea of PLM-like product to its design and discard, to ensure internet security, to train qualified personnel in this matter. As a last word, in a world where high competition conditions exist, the maritime transport sector must continuously follow the technological developments and reshape itself by taking into consideration the needs of the future.

Openings for the sea industry to gotten to be more secure and more effective whereas at the same time diminishing its natural impression. This will make an imaginative exchanging environment, connecting related angles such as the Advanced Economy, Future Cities and modern exchanging frameworks such as Blockchain.

LARG

The Lean, Agile, Resilient and Green (LARG) paradigm was introduced as a framework applicable to the Shipbuilding industry. Actually, this kind of framework has the potentiality to address also the ETO sector more in general. This because at the basis of the various paradigms, Lean, Agile, Resilient and Green are features that are shared among all the industries analyzed: demand and supply uncertainty. In addition, all the sectors share new environmental changes, like ethical and ecological interest of public opinion. The result of the study, which pointed out that Lean and Green were now the two most widespread paradigms, at the light of the previous reasoning, can look quite understandable. It can be more difficult to address why from the literature the Agile paradigm, theoretically suitable in case of huge demand uncertainty, is less considered than Lean. What come out is that in the literature itself there is high uncertainty about the boundaries between one of the other over the others.

Then, it is possible to compare the paradigms with the I4.0 technologies, in particular with Additive Manufacturing. Due to its characteristics like lightweighting, reduction in material usage, reduction in complexity can go beyond the result of Lean and Green.

Anyway, further investigation about this topic is required.

CONCLUSION

This research aimed to be an investigation regarding the main technologies introduced with the coming of Industry 4.0 in Engineer to order sector. What it is possible to address from this work is that the specific industries that compose it are very different in terms of typology of product and service they offer. Nevertheless, from a supply chain point of view, they have important similarities. At this point the thesis tried to understand if Industry 4.0 could represent a possible new way of value generation. In the end, what it was clear is that this field of study is still quite immature and that the Additive manufacturing can address a key role in production. Also, it can represent something interesting to think combining the introduction of these new technologies with.

RESEARCH LIMITATIONS AND FUTURE RESEARCH

This thesis is a critical view on current application of Industry 4.0 technologies in ETO sector. Such theme was not still largely discussed by the most important journals, therefore there is only a limited amount of literature available.

More in general it came out an existing lack a previous analysis of the main issues of the sector, thus it was difficult to understand what were the areas that could be improved through I4.0 introduction.

In addition, the analysis in some cases resulted to stop only at the surface, on a general point of view. Considering the technologies, all the research seemed to be very theoretical, without providing an actual application of them, which would have allowed a better understanding about the benefits derived from their application.

Furthermore, it was not easy to find the common issues of the various sectors of the ETO supply chains. Maybe a deeper analysis regarding commonalities could help addressing in a second stage the most suitable I4.0 technologies, according to their features. Perhaps, identifying the biggest issues could lead to provide a differentiated adoption of LARG, addressing specific paradigms for specific problems.

It was difficult to find out possible real case studies referring to such new topics, to put in support to this work. An analysis of the research methods across all streams of ETO literature confirms that research is predominantly conceptual, with some use of secondary case studies. More testing is required for much of the ETO research. This review highlights further directions for research focused around three themes:

- Further inclusion of other ETO sectors, like oil and gas for example, to address if it is still possible to apply in those cases was found in this work. Therefore, developing a comprehensive definition of ETO supply chains and developing tailored strategies.
- Remaining focused just on the operational viewpoint, future possible researchers from a mechanical and the other from an economical Lack of the financial point of view that maybe could make a technology unaffordable in some cases.
- Case studies and interviews to different ETO companies to understand if the actual implementation level and the main issues they face are in line with our findings.

- Also a further analysis related to the LARG paradigm, trying to apply it in a more general way that would become suitable for the entire ETO sector, something that would make it even more peculiar.

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