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Analysis of implementation of the Design for Manufacturing methodology within Industry 4.0

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Resumen

Durante los últimos años, el desarrollo tecnológico ha marcado un cambio continuo tanto en los modelos de negocio como en los sistemas de producción. Esta transformación es el resultado de la llamada Industria 4.0, la cual nos lleva hacia un nuevo sistema globalizado de interconexión entre máquinas, humanos y sensores donde los límites entre el mundo físico y virtual se desvanecen, dando lugar a un nuevo contexto donde se genera la necesidad de adaptar las metodologías y procesos tradicionales, para que así las empresas puedan seguir manteniendo una posición competitiva en el mercado y satisfacer las demandas actuales.

Dentro de las múltiples áreas posibles de aplicación, este trabajo se ha desarrollado dentro del área de Diseño Industrial, buscando comprender cómo las tecnologías de la Industria 4.0 podrían afectar a la metodología del Design for Manufacturing.

Palabras clave: Design for Manufacturing, Industria 4.0, Diseño Inteligente, Technología, Diseño del Producto.

Abstract

During last years, technological development has marked a continuous change both in business models and production systems. This transformation is the result of the so-called Industry 4.0, which leads us towards a new globalized system of interconnection between machines, humans and sensors where the boundaries between the physical and virtual world vanish, giving rise to a new context where the need to adapt traditional methodologies and processes is generated, so that companies can continue to maintain a competitive position in the market and meet current demands.

Within the multiple possible areas of application, this work has been developed within the area of Industrial Design, seeking to understand how Industry 4.0 technologies could affect the methodology of Design for Manufacturing.

Keywords: Design for Manufacturing, Industry 4.0, Smart Design, Technology, Product Design

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DEPARTAMENTO DE ENGENHARIA MECÂNICA

Análise da implementação da metodologia Design for Manufacturing no contexto da Indústria 4.0

Dissertação apresentada para a obtenção do grau de Mestre em Engenharia e Gestão Industrial

Analysis of implementation of the Design for Manufacturing methodology within Industry 4.0

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Resumo

Durante os últimos anos, o desenvolvimento tecnológico tem marcado uma mudança contínua tanto nos modelos de negócio como nos sistemas de produção. Esta transformação é o resultado da chamada Indústria 4.0, e surge do aparecimento de sistemas que permitem o intercâmbio contínuo de dados, por vezes quase impercetíveis, para um novo sistema globalizado de interligação entre máquinas, seres humanos e sensores onde as fronteiras entre o mundo físico e virtual desaparecem.

A constante evolução da indústria e o aparecimento de novas tecnologias geram a necessidade de adaptar as metodologias e os processos tradicionais a este novo contexto, para que as empresas possam manter-se competitivas no mercado e satisfazer as exigências atuais. Dentro das metodologias de conceção e desenvolvimento de produtos, o Design for Manufacturing é uma das abordagens mais competitiva, graças às quais podem ser alcançadas reduções de custos e prazos de entrega, entre outros benefícios. Com a utilização de tecnologias da Indústria 4.0, estes benefícios podem ser potenciados, uma vez que estes podem ajudar a levar a cabo o processo de conceção de uma forma mais fácil e eficiente. Além disso, os dados do processo de produção são continuamente gravados e armazenados, permitindo assim otimizar processos futuros com base nos resultados de processos anteriores de forma personalizada para a empresa. Portanto, este documento estudará a integraçao da metodologia Design for Manufacturig no contexto da Indústria 4.0, e como as suas tecnologias de habilitação afetariam tanto o processo como o produto final.

Palavras-chave: Design para Fabricação, Indústria 4.0, Design Inteligente, Tecnologia, Design de Produto, Digitalização.

Abstract

During last years, technological development has marked a continuous change both in business models and production systems. This transformation is the result of the so-called Industry 4.0, and arises from the appearance of systems that allow continuous exchange of data, sometimes almost imperceptible, towards a new globalized system of interconnection between machines, humans, and sensors where the boundaries between the physical and virtual world vanish.

The constant evolution of the industry and the appearance of new technologies generates the need to adapt traditional methodologies and processes to this new context, so that companies can remain competitive in the market and meet current demands. Within the methodologies of product design and development, Design for Manufacturing is one of the most competitive approaches, thanks to which cost and lead-time reductions can be achieved, among other benefits. With the use of Industry 4.0 enabling technologies, this benefits can be boosted, since these would help to carry out the design process in a more easy and efficient way. In addition, the data of the production process are continously recorded and stored, thus allowing to optimize future processes based on the results of previous processes in a personalized way for the company. Therefore, this document will study the integration of the Design for Manufacturig methodology within the context of Industry 4.0, and how its enabling technologies would affect both the process and the final product.

Keywords Design for Manufacturing, Industry 4.0, Smart Design, Technology, Product Design, Digitization.

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FIGURE INDEX

TABLE INDEX

ACRONYMS

AI – *Artificial Intelligence*

AM – *Additive Manufacturing*

AR – *Augmented Reality*

CAD – *Computer Aided Design*

CPS – *Cyber-Physical Systems*

DFM – *Design for Manufacturing*

DFX – *Design for X*

EICTS – *Electronics, Information and Communication Technologies*

I4 – *Industry 4.0*

I/O – *Input/Output*

IoS – *Internet of Services*

IoT – *Internet of Things*

RFID – *Radio Frequency Identification Devices*

RTLS – *Real Time Location Systems*

VR – *Virtual Reality*

1. INTRODUCTION

Since the beginning of industrialization, technological jumps have led to paradigm shifts which are now referred to as "industrial revolutions'' (Lasi et al, 2014). Nowadays, industrial production is driven by the high and varying amount of market demand. These changes can be addressed thanks to the emerging fourth industrial revolution, allowing a more flexible production, reducing lead-time, and helping companies to position themselves in the market competitively.

The fourth industrial revolution brings with it the fusion of the physical and virtual world due to the emergence of its new technologies, as in *Internet of Things*, *Big Data*, *Additive Manufacturing*, *Robot Collaboration*, among others. The transition from the traditional processes to the new industrial paradigm is essential, since, apart from the multiple benefits of using Industry 4.0 technologies, only by embracing them is it that companies will be able to stay in the future market

Within its multiple areas of application, this work will be developed in the area of industrial product design, and aims to understand how Industry 4.0 technologies could affect the Design for Manufacturing methodology.

1.1. Background

From a historical point of view, the first industrial revolution started with the invention of the steam engine, in mid-18th century, using water and steam for mechanical production. We find the second industrial revolution in the early 20th century, with the invention of the internal combustion engine, adventing assembly lines and mass production. Finally, in 1970s, the automation of production through electronics and information technology led to the third industrial revolution (Nascimento et al, 2018).

The fourth industrial revolution, a term coined by Klaus Schwab, founder and executive chairman of the World Economic Forum (Miller, 2015), began with the apparition of the cyber-physical systems (CPS), term which refers to the computer-integrated manufacturing, led by the development and integration of the systems from the third industrial revolution (Nascimento et al, 2018).

Period	Transition Period	Energy Resource	Main Technical Achievement	Main Developed Industries	Transport Means
I: 1760-1900	1860-1900	Coal	Steam Engine	Textile, Steel	Train
II: 1900-1960	1940-1960	Oil Electricity	Internal Combustion Engine	Metallurgy, Auto, Machine Building	Train, Car
III: 1960-2000	1980-2000	Nuclear Energy Natural Gas	Computers, Robots	Auto, Chemistry	Car, Plane
IV: 2000-	2000-2010	Green Energies	Internet, 3D Printer, Genetic Engineering	High Tech Industries	Electric Car, Ultra-Fast Train

Source: Prisecaru, P. (2016). "Challenges of the Fourth Industrial Revolution." *Knowledge Horizons. Economics*, 8(1), 57-62. Web https://search-proquest-com.ezproxy.libraries.udmercy.edu:2443/docview/1793552558?accountid=28018.

Table 1. Main characteristics of the industrial revolutions (Xu et al, 2018).

1.2. Motivation

Due to digital transformation, industry and the way of working is changing, and, in order to stay competitive, companies have to adapt to these changes, transforming work processes and looking for new models that include the implementation and use of digitalized processes. A whole set of new design principles must be acquired in order to reach intelligent products and manufacturing (Porter et al. 2014).

We can find different work methodologies within Industrial Design and Product Development, of which Design for Manufacturing is one of the most effective and used approaches. The use of this methodology carries numerous benefits, such as cost and lead-time reduction, so the motivation of this work is to explore how implementing Industry 4.0 technologies could boost those benefits and improve the results obtained.

1.3. Objectives

The objective of this research is to explore how industrial product design processes, and, more specifically, how the Design for Manufacturing methodology can be affected by the by the fourth industrial revolution (also known as Industry 4.0), comprising its implementation requirements and conceptual framework as its barriers and benefits.

In order to achieve this, it is first needed to comprehend what Industrial Design and the methodology of Design for Manufacturing are, as well as comprehend what is Industry 4.0 and its enabling technologies.

1.4. Structure

This document is sectioned into five chapters, counting introduction and conclusions, which are as follows:

Chapter 1 is an introduction, where the context of work, motivation, objectives and structure of the dissertation is presented.

Chapter 2 explains the methodology of search, selection and analysis of articles followed for the realization of the document.

Chapter 3 develops the concepts of Industrial Design and Development of Products, Design for Manufacturing, and Industry 4.0.

Chapter 4 begins to explore the new direction DFM could take in the context of Industry 4.0, starting with the implementation requirements to face and the conceptual framework, and then presenting in which part of the process would be implemented and the possible benefits and barriers of implementation, in addition to some examples of use of the technologies of the fourth industrial revolution within this methodology.

Chapter 5 presents the conclusions drawn by the development of this work.

2. METHODOLOGY

The method used to carry out this document is from a different indole according to the different sections. To begin with, we find an analysis of concepts, which aims to understand the terms used for the development of the subsequent study. In this first part, we explore our understanding of concepts as Industrial Design and Product Development, Design for Manufacturing and Industry 4.0, for which the relevant information encountered in different documents have been read, analyzed, synthesized and redacted.

Aditionally, and taking into account the terms previously analyzed, it is explored the benefits and barriers for the implementation of digital technologies of Industry 4.0 in the Design for Manufacturing methodology. In order to achieve this, documents addressing similar approaches have also been read, synthesized and redacted.

2.1. Search strategy

In order to conduct this study, diverse research pages have been consulted, such as *Scopus*, *GoogleScholar* or *ScienceDirect*, in which scientific articles, book chapters, written records of conferences, scientific magazines, etc, have been found. Apart from this search, some of the papers used for this study have been taken from the bibliography of some of the documents previously selected.

The keywords used on the research pages mentioned above are the following: Product Design, Industrial Design, Design for Manufacturing, Design for manufacturing and Assembly, Industry 4.0, Fourth Industrial Revolution, New directions, Smart Manufacturing, Virtual Reality, Artificial Intelligence, Automation, Additive Manufacturing, Big Data, and Challenges. Numerous searches were done, using different combinatios with the keywords depending on the field of study which was required,

2.2. Selection criteria

Several articles were selected in a preliminary way if the title was considered of interest for the development of this document.

However, they were not definetly selected for use until reading the abstract of the documents and browse its contents, in order to guarantee that they were going to be of use. As a result, out of the 73 documents previously selected, only 48 were used for the development of this research.

Within these documents, 5 were books, 8 excerpts from conferences, 28 scientific articles within journals, 1 tesis, 2 working papers and 4 undefined scientific articles are found (Figure 1). Out of those, 11 were about Design for Manufacturing, 16 about Industry 4.0, 3 about Industrial Design and Product Development, 6 about design in Industry 4.0, 9 about manufacturing in Industry 4.0, and 3 about Design for Manufacturing in Industry 4.0 (Figure 2).

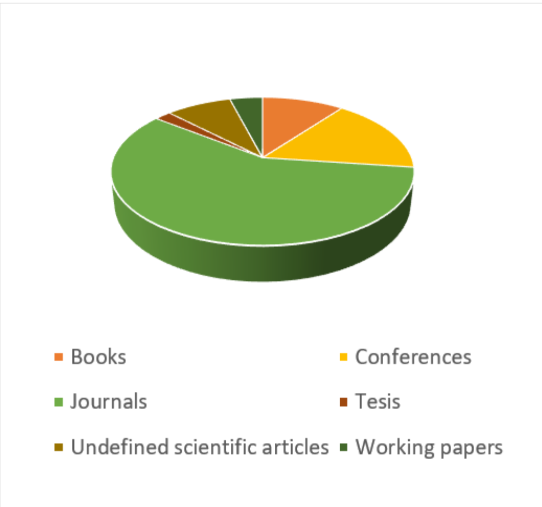

Figure 1. Type of documents.

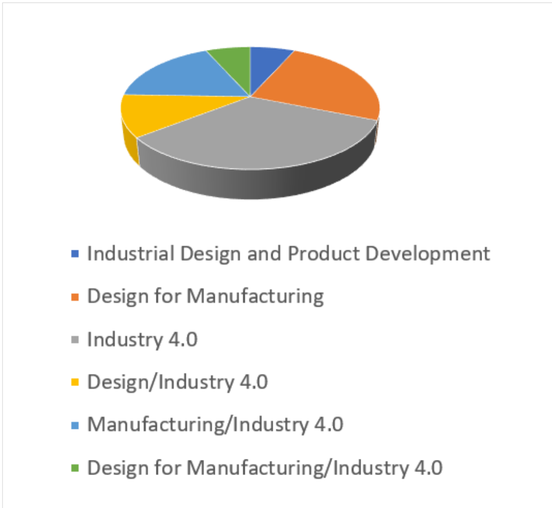

Figure 2. Content of documents.

2.3. Analysis and syntesis of the documents

To conclude, all the selected documents were read an analysed, highlighting relevant information, taking notes and connecting ideas in order to reach conclusions.

Information about the concepts of Industrial Design and Product Development, Design for Manufacturing and Industry 4.0 was searched in order to have a proper understanding of the terms with which the research was going to be carried out. Once this was completed, the second phase consisted on reaching own conclusions about the implementation of Design for Manufacturing within the fourth industrial, while reading in contrast proposals from other authors in similar fields.

3. ANALYSIS OF CONCEPTS

3.1. Industrial Design and Product Development

"Industrial Design and Product Development is the field of knowledge that is responsible of conception and development, from the moment of its idea to its final evaluation, correction, and conclusion, of objects and products to be manufactured with a functional purpose, taking into account economic, functional, aesthetic and commercial factors and limitations, and involving numerous branches of knowledge, working with multidisciplinary teams" (Viaedu, 2019).

When it comes to Industrial Design, its beginnings date back to the 18th century, with the first industrial revolution and the substitution of manual work for machines. Before this, it was the craftsman who took care of the production process, simultaneously carrying out design and production, but with the industrialization of manufacturing and use of machines, defining all the details before the production was necessary, since no changes could be made once the production process started. One of the first who began to consider this was Michael Thonet (1796-1871), recognized name and referent within the industrial design area, craftsman founder of furnitures Thonet, a mass production manufacture of curved wood furniture by chemical or mechanical procedures. He also started to seek comfort and highlight the advantages of the fineness and lightness of the design against solid furniture (Gay et al, 2004). Another name to highlight is Henry Cole (1808-1882) founder of Journal of design and manufacture, first journal of design, where eliminating the gap between the artist and the industrial was sought, putting function before aesthetics, thus beginning a new reform movement (Alzaga et al, 2016).

Aside from these approaches, it wasn't until the Great Exhibition of the Works of Industry of all Nations, first exhibition of industrial products that was held in London in 1851 this subject started to sprout, owning to aesthetic quality being questioned due to the mismatch appreciated between shape and ornamentation of the products presented.

Searching for a solution, various researches were done, leading to what we know today as Industrial Design, searching to conciliate, as shown in Figure 3, aesthetics with the utilitarian function and technologies, taking into account formal factors, function, aesthetics, constructive and economic factors, ergonomics, legality, among others, to meet technological and market needs. Because of this, before designing the product, it has to be done an analysis of social and economic requirements, of what has to express the product shape and what is its function, of the formal user, of the materials and of the construction techniques. (Gay et al, 2004).

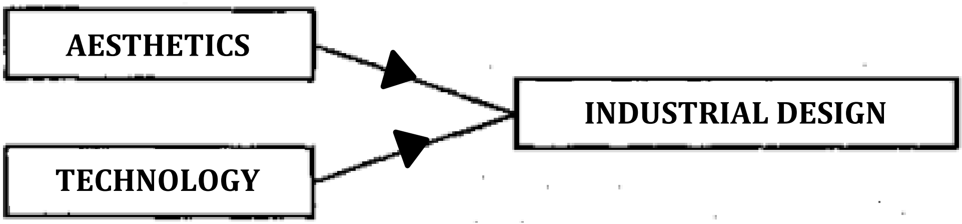

Figure 3. Where Industrial Design comes from (Gay et al, 2004).

Industrial design objects are born in response to needs or demands of society, and they are oriented to industrial production. The model of the proposed process by Pahl et al (1995) is described as follows:

- Planification of the design of the product: Analysis to gather the information mentioned before (functional and economic requirements, potential users…).
- Phase of the conceptual design: Define the basic problem, working steps and functional structure in order to narrow down and reach a main solution.
- Phase of the design of the assembly: Where technological and economical requirements are taken into account (functionality, spacial compatibility…)
- Phase of the detailed design: Technical drawings are defined and described, as the materials, techniques… It gathers the 70-80% of the design activity of the industry.

After all of this is done, the design has to be validated via prototyping, to check if the designed product has the correct functionality. Once the design is validated, the product can start to be manufactured. Its production process can be designed via simulation, with the use of conceptual, graphical, physical or mathematical models, to evaluate different hypothesis. Once you have a reliable model, the functionality and behavior of the real model can be evaluated (Toledo et al, 2016). Both this phase and the previous ones mentioned are depicted in the flowchart from Figure 4.

The final step on the product design process is the elaboration of the documents of the product, which are:

1) Memory and annexes;
2) Technical drawings;
3) Condition and particular technical requirements specifications;
4) Measurements;
5) Budget.

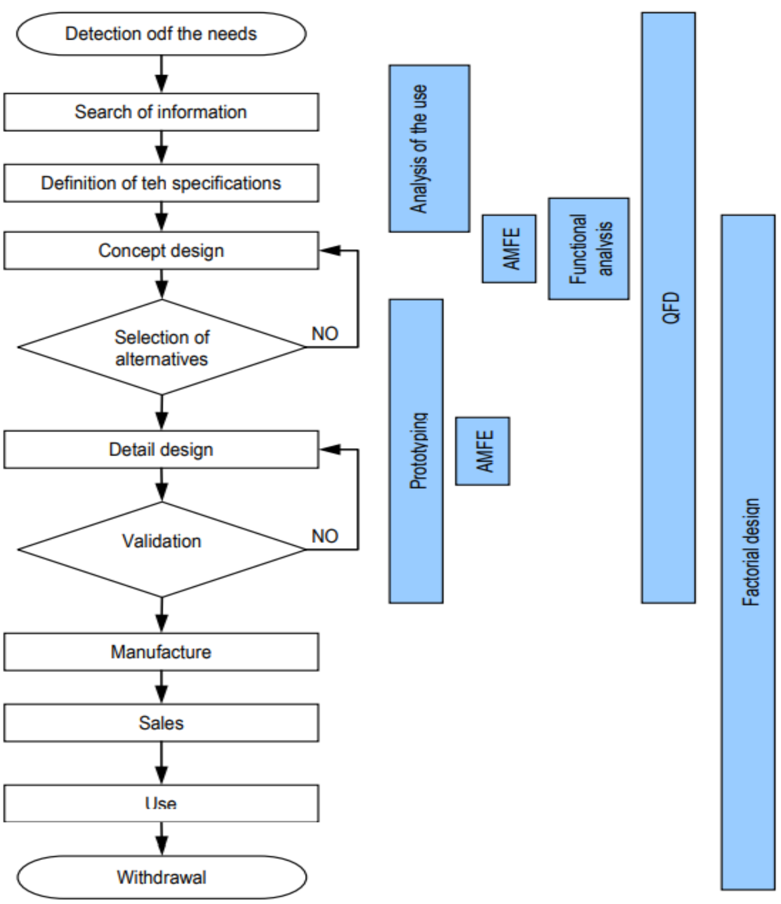

Figure 4. Phases of the design process (Toledo et al, 2016).

All of this process is influenced by theoretical technical and practical knowledge, either for the elaboration of the design itself focused on the user experience and its use or for its technical and practical development through engineering knowledge and other matters. (Esdima, 2022).

3.2. Design for Manufacturing

In order to help designers during the design process and in the product engineering stages, manufacturers and researchers developed different Design for X methods (Favi et al, 2016). The X on DFX stands for the multiple targets or design considerations for the product, such as cost, performance, sustainability, or quality, among others.

Design for Manufacturing is one of the most commonly used DFX design tools (Hermann et al, 2004). It arises from the successful application of Design for Assembly in manufacturing, and it is associated with the identification of the proper materials and manufacturing process to improve or develop products and the performance of the production systems (Kuo et al, 2001; Ulrich et al, 1993). According to Boothroyd (1996), its purpose is to estimate costs so that design teams can consider “alternative design and production processes, quantify manufacturing costs, and make necessary trade-off decisions between part consolidation and increased material/manufacturing costs”. It contributes to reducing time and cost during the product design phase to maintain competitiveness in the market (Wang et al, 2021).

Figure 5 shows, according to O’Driscoll (2002), a typical flowchart of the DFM methodology, where it can be seen how the design process is carried out on par with the manufacturing and material requirements, as its iterative nature, since it is a process that is repeated until the best design for ease of manufacture is achieved.

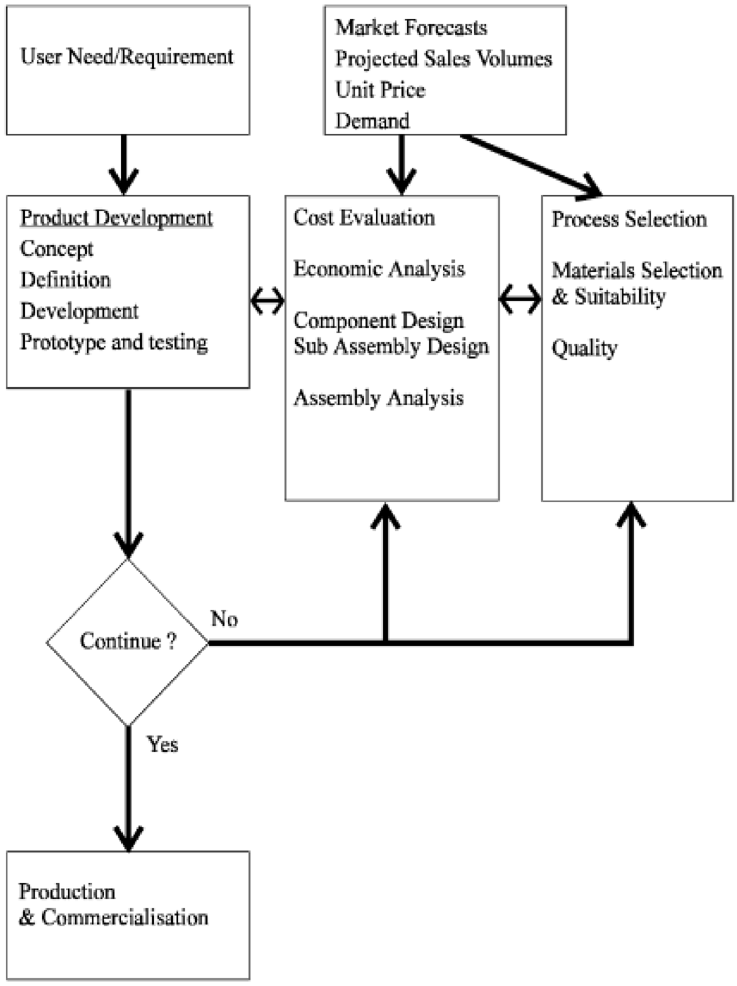

Figure 5. Typical DFM flowchart (O'Driscoll, 2002) .

This concept first appears in 1788, with the proposal of LeBlanc on using interchangeable parts in the manufacture of muskets. This resulted on a development of basic manufacturing processes for repeatability instead of continuing with craftmanship, which gave rise to a quicker, cheaper, and more reliable manufacturing. Despite this, it wasn't until the 20th century that the term became known (O'Driscoll, 2002).

In the early 1960, producibility guidelines were developed in order to help designing products for the ease of manufacturing, but later some of them have been proven wrong, due to spreading misconceptions. One of the most common spread misconceptions, depicted in Figure 6, is about the belief that several simple-shaped parts would be less expensive to manufacture than a single complex part.

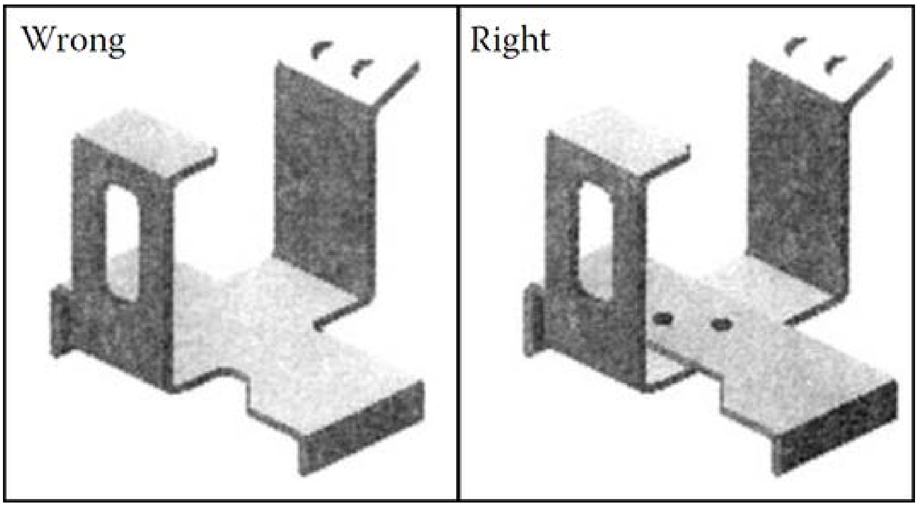

Figure 6. Misleading guideline spreaded in productibility guidelines (Boothroyd, 2002).

	Wrong	Right
Setup	0.015	0.023
Process	0.535	0.683
Material	0.036	0.025
Piece part	0.586	0.731
Tooling	0.092	0.119
Total manufacture	0.678	0.850
Assembly	0.000	0.200
Total	0.678	1.050

Table 2. Estimated costs in dollars for the two examples in **Figure 4.** if 100,000 units are made (Boothroyd 2002).

Some shop floor courses also appeared to help designers on getting familiar with manufacturing processes, so they could avoid adding unnecessarily manufacturing costs, but they eventually disappeared since the university did not consider them suitable as a course. Having designers who are not competent on the manufacturing processes resulted on manufacturing engineers, whose labor is to optimize the processes, encountering problems on the drawings when they have them passed from the designers, causing considerable delays in the final product release due to all the design changes that have to be made. Even though it is extra time spent in the early design process, considering manufacturing during the early stage of product design results on saving time when prototyping and reducing the lead time, in addition to the saving costs of materials, energy and human resources. (Boothroyd, 2002).

Nowadays, DFM has become a very important issue when it comes on designing products. In opposition of the previous paradigm, which sought standardization of the product, customization and diversity have become one of the main aspects required from designers and customers (Chu et al, 2016). Products are becoming more and more complex and an increase in quantity and quality is demanded. The increase in demand has led to mass production, thus obtaining a greater number of products in a shorter period. In addition, it is required to satisfy a higher population percentile, so these production lines should also be flexible (O' Driscoll, 2002).

3.2.1. Objectives of DFM

In order to achieve a successful implementation of DFM, there are a set of objectives to achieve, summarized by Wang et al (2021) as follows:

- Improve reliability, reduce purchasing, and inventory costs by minimizing the number of steps, parts and linkages. In order to reduce parts, there has to be done three re-configurations: component elimination, component combination, and abstract combination of both of the proposed techniques.
- Reduce costs and lead time, by developing a modular design and the use of standard components.
- Reduce labour costs, by considering design for automation or robotic manufacturing.

As Chu et al (2016) determine, it is searched an "assembly design with a minimum number of parts, standard parts, modular design, and multi-functional parts, making parts standard for multiple products, maximum surface roughness and tolerance, avoiding secondary processes, using materials that are easy to manufacture, minimizing the handling of parts, and setting the guidelines of design and shape."

The selection of the proper materials and processes for the manufacture on an early design stage is fundamental, and although it is based upon the matching of the required attributes of the part and the various process capabilities (including raw material selection, and process selection) (Kuo et al, 2001), it also depends on which manufacturing process and materials is the design team more comfortable with. The more knowledge available and encompassed by the designer, the better designs can be reached, due to their greater awareness and understanding of the materials and processes they could be working with (Howard and Lewis, 2003). Figure 7 and Figure 8 show two surveys made to designers to check respectively their knowledge about manufacturing processes and polymer materials, being the white bar that they know great deal or fair amount about them, and the black bar that they know little or nothing.

According to Howard and Lewis (2003), a few examples of the information to be considered in terms of selecting materials/process combinations:

1) Product life volume;
2) Permissible tooling expenditure;
3) Possible part shape categories and complexity levels;
4) Service requirements or environment;
5) Appearance factors;
6) Accuracy factors.

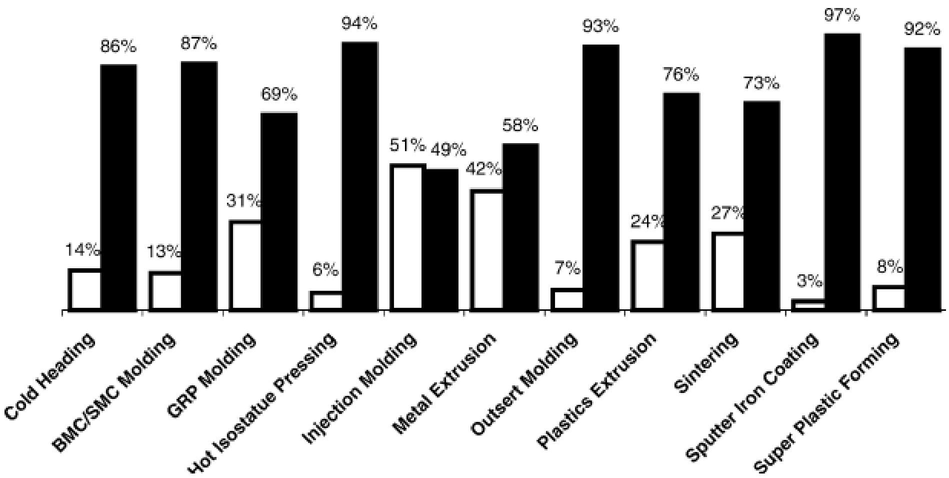

Figure 7. Survey of designers knowledge on manufacturing processes (Howard and Lewis, 2003).

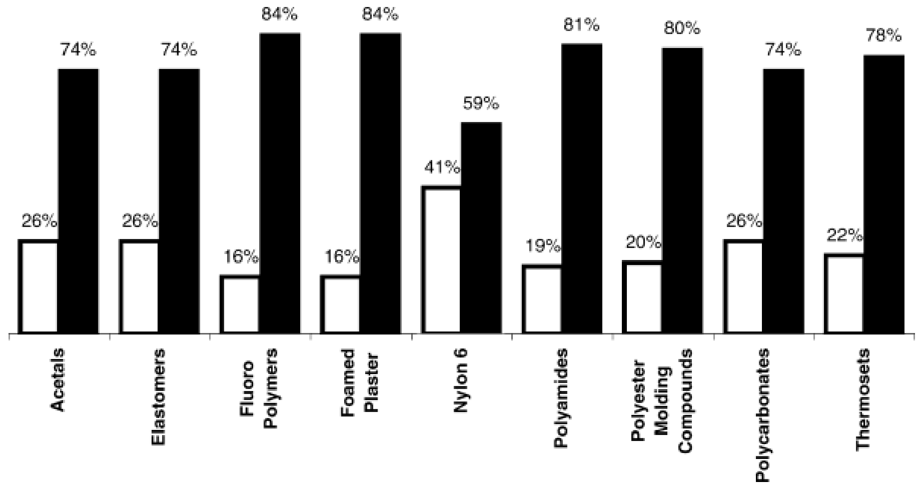

Figure 8. Survey of designers knowledge on polymer materials (Howard and Lewis, 2003).

3.2.2. Benefits of implementation of DFM

As it has been previously exposed, the implementation of the DFM methodology within the design and development of products brings with it various benefits, enhancing the performance of product design and development. Some of those benefits will be developed in this section (Wang et al, 2021; Moeeni et al, 2022; Chu et al 2016).

The main benefits provided by the implementation of this methodology are cost and lead-time reduction. It has been shown that, although only 10% of the total budget for a new project is consumed by the design cost, product design determines 80% of the manufacturing costs (Favi et al, 2016). Designing a product for the ease of manufacture will allow not having to do reworks, and therefore, it will result in a cost reduction, avoiding this way additional cost of material, electricity, and human resources, in addition to resulting on a faster process, thus reducing lead-time. Another benefit is the achievement of a better process schedule thanks to the detailed manufacturing planning and its corresponding completion periods, thus allowing designers, manufacturers, and consumers to have a clear idea of the time it will take to carry out the processes. Using the DFM methodology from an early stage of the product design also tends to reduce part count, by component combination and/or component elimination techniques. According to Moeeni et al (2022), part count reduction is the best way to reduce costs, due to reductions in purchasing, inventory, and shipping, in addition to reducing production time and process difficulty.

A proper planning of the use of the resources to be used from the beginning of the product design and development process will result in an optimization of its use, thus obtaining a better use of them. It also helps on avoiding mistakes and failure during production processes, since thanks to the correct planning of resources, industrial designers can more easily detect possible errors during the production process or dew the wrong use of materials, thus being able to minimize or even avoid or eliminate them. Owing to this better use and consciousness of the resources available, productivity is enhanced, and an improvement of the quality of final product is obtained, thus increasing customer satisfaction. This increase in quality together with the reduction in time and cost allows companies to position themselves in a more competitive way in the market, obtaining a better and more differentiated product as wining costumers and boosting profitability (Technosoft Engineering, 2020).

Benefits of Design for Manufacturing	Cost and lead time reduction	Avoidance of reworks
		Detection and elimination of errors
		Detailed manufacture schedule
		Better planning of resource usage
		Part count reduction
	Sustainability	Optimization of resource usage
		Decrease of waste
	Customer satisfaction	Increase of product quality
		Cost and lead-time reduction
	Greater competitiveness in the market	Increase of costumers
		Increase of productivity
		Differentiated product

Table 3. Benefits of Design for Manufacturing.

3.2.3. Barriers of implementation of DFM

The main barrier for DFM implementation is the humans themselves. Although there are some people willing to accept changes and try new ways of working, most of them tend to resist unfamiliar methods, claiming their method to be effective and with no further changes to be required. Companies would have to carry out training courses for the current designers so that they achieve a greater knowledge in the area of manufacturing, which would result in time and money cost, or look uniquely for designers with that profile. Moreover, aside from their capabilities, in order to achieve the best design for the ease of manufacture, it would be best for the designers to collaborate with manufacturer engineers. This entails problems concerning communication and the ability to share knowledge between them, since their different skills are reflected in their different way of working and approaching problems. In the event that manufacturing engineers are not available, the area of choice of materials and manufacturing processes would be reduced to those with whom the design team feels more comfortable working with, as previously explained, thus depriving the use of materials and production processes that could be of interest in order to get more benefits.

Another problem when implementing DFM is time. Designers are constantly pressured and chased by deadlines. Consider manufacturing from an early stage in the design process would imply more time needed for designers to work. Therefore, a change on the mentality of the companies would be necessary, allowing this extra time for designers to achieve the desired design with manufacturing in mind, which is critical in order to reap benefices later. Despite this, it must also be considered that it is not always possible to determine all the details of the manufacturing process with certainty, such as the cost of manufacturing and materials, representing this another concerning barrier of implementation, since an error in this could result in an unexpected increase in the total cost when going to manufacture the designed product (Hermann et al, 2004; Boothroyd, 1996; Howard and Lewis, 2003). The automation of production processes aggravates this, making the redesign of the product in the face of a mistake become even more costly in time and money (Mital, 1994).

Barriers of Design for Manufacturing	Resistance to change	Accustomedness
		Unwillingness of accepting new ways of working
	Collaboration with manufacturing engineers	Communication problems
		Manufacturing engineers may not be available
	Knowledge	Reduced area of choice of materials and manufacturing processes
		Lack of extensive knowledge about materials and manufacturing from some designers
	Designers' deadlines	Change of mentality
		Increase time on design stage
	Uncertainty about some details	It is not always possible to determine all materials and manufacturing processes in detail
		Unexpected increase on total cost due to planning errors

Table 4. Barriers of Design for Manufacturing.

3.3. Industry 4.0

This term, coined in 2011 in Germany, refers to the industrial revolution in which we find ourselves today, the fourth industrial revolution. It consists of the integration in the production processes of electronic, information and communications technologies (EICTs), improving levels of automation and making the industry smarter (Lizarraga, 2018). It can also be referred as *Factory of the Future*, or *Smart Factory* (De la Fuente and Mazaeda, 2016).

Industrial Revolutions are economic and technological transformations that have occurred over time, which had a significant impact on society and its functioning. The first industrial revolution dates back to the XVIII century, with the invention of the steel machine, which led to a mechanization of the production processes, thus moving from a predominantly agrarian and artisanal economy to an industrial economy. Almost a century later, the second industrial revolution takes place, bringing with it the division of labor in assembly lines and mass production, due to the advances in the chemical, electrical, oil and steel industries. During this stage, new sources of raw materials an energy also started to be used. The third industrial revolution began in the late 20th century, with the use of electronics and informatics technologies in the production process to achieve automation in repetitive tasks (Del Val, 2016; Pereira and Walmir, 2020).

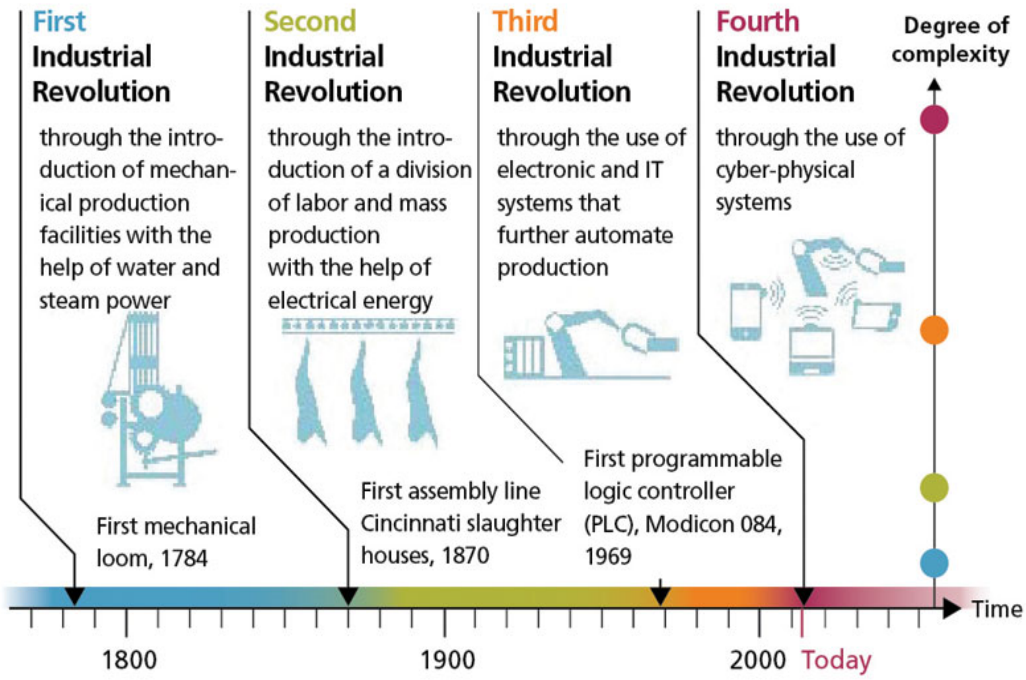

Figure 9. Industrial revolutions over time. Retrieved from https://www.inceptra.com/the-evolution-of-model-based-systems-engineering-in-product-development/

3.3.1. Design principles

There is a set of six design principles to help transitioning from Industry 3.0 and achieve implementation of Industry 4.0, explained in the following section (Pereira and

Walmir, 2020; Díez, 2021; Hermann et al, 2015; King, 2021):

- Interoperability: Constant communication between machines, sensors and people thorough IoT is sought, along with facilitating exchange of information and control of actions in an autonomous way thanks to intelligent machines and intelligent storage systems brought by CPS. This is one of the most important enablers of Industry 4.0.

- Virtualization: There must exist a digital image of everything in order to see what happens during the manufacturing process at any moment, sharing, saving and synthesizing information in real time so it remains available to aid human work when necessary. According to King (2021), in virtualization we can find two scenarios: "One virtual resource created from multiple physical resources", through the creation of digital twins of physical objects; and "many virtual resources created from one or more physical resources", where one physical server is divided into multiple cyber-servers that act separately.

- Decentralization: Machines must have the capacity of automated decision-making, providing more flexibility and ease of use, and thus breaking with traditional use of central-computer management and hierarchical delegation of decision-making. This also results in manufacturing operators with greater freedom when it comes to identifying and analyzing parameters and aspects, as well as making decisions over the process and machines.

- Real time capability: In favor of making decisions at every moment of need and giving the best response time to internal and external stimuli as seeing possible improvements in the production processes and productivity opportunities, having real time-data collection and processing is needed. Real-time capability also helps on managing malfunctions before they have major consequences minimize misuse of resources and energy, material waste…

- Consumer oriented: Nowadays, there is a need of adaptation to customer changing needs and market demand, given the wide variety of products in demand. Via IoT and Big Data, users can have access to services, products, and industry information, thus allowing a personalized service and resulting in a shift from mass production to consumer-oriented production.

- Modularity: The use of modular systems brings the ability to change and adapt to the new market by replacing or expanding individual production models. Thus, it will be easier to quickly adapting and responding to increases and/or changes in market demand.

3.3.2. Core components

In Industry 4.0, the merge of the ECITs in the production processes results in a changeover from traditional industry, evolving to a smarter factory due to the constant flow of data and the interconnection between machines, humans, and sensors. According to Mohamed (2018), the core components that form the fourth industrial revolution and allow this change are the following:

1) Radio Frequency Identification (RFID systems): Allow to identify the processing goods thanks to data transmitted via radio waves.

2) Real Time Location Systems (RTLS systems): Systems that make possible identification the location of the processing good in real time.

3) Cyber Physical Systems (CPS): Intelligent devices with computing and communication capabilities that interpret and learn from the physical world by interacting with it. This merging of digital and physical workflows gives rise to distributed and autonomous ecosystems (Pereira and Walmir, 2020).

4) Networking or Internet of Things (IoT): Allows reaching automation and real-time capability due to its constant connection between machines, sensors, and people (Del Val, 2016; Pereira and Walmir, 2020; Díez, 2021).

5) Data collection and analysis: Advancement of technologies has caused an increase of variety, volume, and data creation, for what devices that are capable of receive, processing and storing that information are needed.

6) Business Service or Internet of Services (IoS): Virtual infrastructures for services that allows vendors to offer their services via Internet.

3.3.3. Other enabling technologies

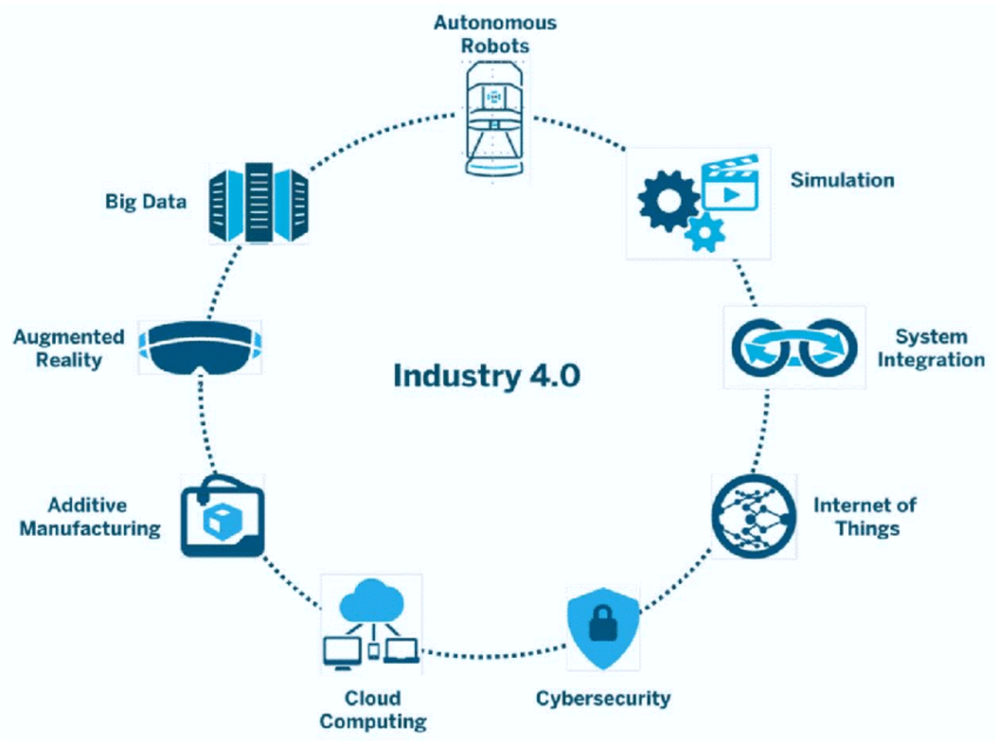

Figure 10. Some of the enabling technologies for Industry 4.0. Retrieved from https://medium.com/@shalinisreekanth/industry-4-0-the-top-9-technology-trends-28c1b3cf1a9a

3.3.3.1. Big Data

Big data refers to a set of data which is not suitable for traditional data processing methods due to their complex structure, wide range of formats, and large scale, for which are required technical, and specialized systems and methodologies, such as analysis, capture, data management, storage, transmission, visualization, or data protection to perform, among other things, predictive analytics, extract data value, and target specific sized datasets. (Seok et al, 2016).

Its objective is to have a better management of available resources, using the description, prediction and optimization models mentioned above to take more effective decisions (Lizarraga, 2018).

3.3.3.2. Additive Manufacturing

Via Additive Manufacturing (AM) 3D models, such as CAD files, can be converted into physical objects by bonding or connecting materials using light, ultrasonic vibrations, lasers, and electron beams. Depending on the material or bonding method, the part resulting would have different properties (Seok et al, 2016). Some of the techniques used are photopolymerization, material extrusion, powder bed fusion, or binder jetting.

It was originally used as rapid prototyping to realize product ideas of design engineers, but nowadays, due to the advances in materials and lamination technology, it can also be used for manufacturing complete products (Seok et al, 2016), or in conjunction with other manufacturing processes (Campbell et al, 2012). It is used into various fields, such as aviation, vehicles, clothing, and biomedical (Seok et al, 2016).

3.3.3.3. Artificial Intelligence

Artificial intelligence (AI) is the ability of a computer, or a robot controlled by a computer to do tasks that are usually done by humans because they require human intelligence and discernment. The term is frequently applied to the project of developing systems endowed with the intellectual processes characteristic of humans, such as the ability to reason, discover meaning, generalize, or learn from past experiences (Copeland, 2022).

3.3.3.4. Virtual Reality

Virtual environment created by technology that allows to transport ourselves to it through immersive technologies and live experiences similar to reality (García, EDSrobotics, Ibedrola, 2021).

According to Peng (200-), we can summarize the features of VR as “three I’s”

- Inmersion: Although the user is in a virtual environment, it feels like the real world.
- Interactivity: Advanced I/O devices that allow to interact with the virtual environment created.
- Information intensity: All human senses information is used.

3.3.3.5. Augmented Reality

AR consists in real-time use of virtual enhancements, like text, graphics or audio, integrated with real world objects, adding value to the user’s interaction with the real world (Uglovskaia, 2017). According to Hamilton et al (2020), this is achieved by using a system related to a camera, a GPS system, a 3D scale, and an algorithm that bonds the virtual stimuli with reality.

3.3.3.6. Cobots

Although they have been applied in the industry for many years, robots in the Industry 4.0 are needed to be more flexible, autonomous and cooperative, thus being able to perform more complex actions. It is sought that they are able to interact with each other and with humans, in addition to learning from their actions (De la Fuente y Mazaeda, 2016).

3.3.3.7. Cloud Computing

An Internet-based technology that offers a new way of sharing the data and information generated, where a shared group of configurable computing resources is located (eg. networks, servers, applications and services). It allows to introduce and release these resources quickly and with minimal management effort (Xu, 2012).

3.3.3.8. Digital twin

Technology that makes possible the convergence between physical and virtual spaces. A virtual image of a physical entity, which records the history performance of the physical one and carries out optimization and prediction for it, is created, while physical entity provides the rules and behavior for the virtual model to follow, thus evolving and calibrating it continuously (Tao and Zhang, 2017).

3.3.4. Benefits of implementation of Industry 4.0

Current value chains are evolving, and so is business, due to emergence of new innovative models and integration of smart products with smart production and smart networks. Therefore, the smart factory will be key to the infrastructures of the future, bringing several benefits with it (Mohamed, 2018).

According to Uglovskaia (2017), one of the benefits brought by Industry 4.0 and smart factories to the companies would be advanced planning and controlling with real-time data, due to the ability to acquire and organize Big Data. Industry would be also able of having a more rapid reaction to changes in demand, thanks to modularity, resulting on a higher quality of product manufacture and more flexible production. In addition, it will also provide quick responses against any other event that occurs in the production line, such as stock levels or errors. This rapid reaction to industry variables provokes a decrease in lead time, and together with the increase of higher quality mentioned before, a more sustainable manufacturing is acquired in terms of optimization of the use of materials, energy and people, thus reducing costs and waste; and its ability to adapt to market changes and demand variation allows personalizing products according to customer needs, reaching new levels of customer satisfaction (Waibel et al, 2017; Ugokslavia, 2017).

Apart from those advantages in terms of production processes, companies would also obtain benefits on a personal level, reaching safer work conditions thanks to being able of recreating possible dangerous work situations on a virtual environment in order to see its behavior before recreating in real life. If that critical operation is being already carried out physically, automation and the capability of quick reaction from the device to any error would also reduce occupational risks. Work-life balance would also be easier to manage, thanks to the decentralization feature of smart factories. To sew up, companies would also achieve benefits in terms of its image (Waibel et al, 2017; Ugokslavia, 2017).

Benefits of Industry 4.0	Cost and lead time reduction	Advanced planning and controlling
		More rapid reaction to stock levels and errors
		More rapid reaction to changes in demand
	Sustainability	Optimization of resource usage
		Waste reduction
	Human resources	Safer work conditions
		Easier management of work-life balance
	Customer satisfaction and market competitiveness	Quick adaptation to market changes
		Increase of product quality
		Product personalization

Table 5. Benefits of Industry 4.0.

3.3.5. Barriers of implementation of Industry 4.0

Despite the multiple benefits that implementation of Industry 4.0 brings, there are still certain barriers and challenges to overcome to achieve it. These barriers, according to Raj et al (2020), still remain highly unexplored in the current available literature, and requires further investigation.

The main barrier that hinders the application of Industry 4.0 is directly incumbent on human resources, this being the lack of skilled workforce. New technologies require new competences and new ways of working, and in order for workers to acquire the knowledge and skills to manage digital technologies, money and time has to be spent. In addition, given that technology is continuously evolving, it won't be enough just to take courses, so there will also be a need for continuous learning and on the job training. This lack of skilled workforce also results in leaders without the appropriate skills, competences, and experience, given the lack of time in the face of the novelty of technologies.

Financial resources are also an important problem for its implementation. According to Geissbauer et al (2014), companies would have to increase for five years their investments up to 50% in order to achieve Industry 4.0 implementation. This implies that a huge investment has to be done in order to acquire the digital technologies and transform its current industry model, in addition to the learning courses for workers for workers to acquire the aforementioned skills. This would be viable if there were a certainty about getting the investment back, but there is still a lack of clarity regarding productivity gains and economic benefits. Technological integration is also a major problem, given the need of a flexible interface to synchronize the different languages, technologies, and methods. Furthermore, there would be a need for large amounts of storage capacity, additionally to safer storage systems. There is a huge concern about cybersecurity and data ownership, fearing breaches of personal data and private information. Systems reliability and stability must also be ensured. Another problem concerning technologies is the lack of standards and regulations. Given the continuous technological advances, they have to be adapted quickly to these changes in order to satisfy the client interests (Kumar and Kumar, 2020; Raj et al, 2020; Horvath and Szabo, 2019).

Other barriers to be considered are given by the resistance and cultural acceptance of Industry 4.0, since it would bring a disruption in the current existing jobs and social changes. Many workers refuse to use new technologies, either because of their apparent complexity or because of their accustomedness and reliability in the technologies with which they previously worked (Raj et al, 2020).

<table>
<tr><td rowspan="13">Barriers of Industry 4.0</td><td rowspan="3">Human resources</td><td>Lack of skilled workforce</td></tr>
<tr><td>Need for new competences</td></tr>
<tr><td>Need for training courses and continuous learning</td></tr>
<tr><td rowspan="2">Financial resources</td><td>Huge initial investment</td></tr>
<tr><td>Uncertainty about benefits and profitability</td></tr>
<tr><td>Management</td><td>Leaders with appropriate skills</td></tr>
<tr><td rowspan="4">Technology integration</td><td>Need for large amounts of storage</td></tr>
<tr><td>Lack of trust in the systems</td></tr>
<tr><td>Lack of standards and regulations</td></tr>
<tr><td>Concerns about cybersecurity and data ownership</td></tr>
<tr><td rowspan="2">Resistance to change</td><td>Disruption on current jobs</td></tr>
<tr><td>Accustomedness to tradition</td></tr>
</table>

Table 6. Barriers of Industry 4.0.

4. DESIGN FOR MANUFACTURING IN THE NEW INDUSTRIAL REVOLUTION

The speed and measure of the changes brought by the fourth industrial revolution cannot be ignored. These changes will bring about shifts in power, shifts in wealth, and knowledge; and we can only ensure those advances in knowledge and technology and reach benefits from them by understanding these changes and the speed in which they are occurring (Xu et al, 2018). We must evolve with these changes and so the industry has.

Manufacturing is becoming increasingly automated and digitalized. This means that the design of products must take into account the capabilities of the machines that will be used to manufacture them. As products become more complex and customer demand becomes more volatile, manufacturers need to be able to quickly adapt their production lines to meet changing needs and benefit from the digital revolution. Intelligent manufacturing uses advanced manufacturing and advanced technologies in order to reach those needs and optimize the production and product transactions, transforming the design, production, management and integration of the life cycle of a typical product (Zhong et al, 2017; Celaschi, 2017). There will be constant connection and communication with the product and the machines throughout the production process, allowing to intervene in any situation and even to be able to make interruptions and last-minute changes within the manufacturing operations (Lee et al, 2015).

Although there is still no defined frameworks, Figure 11 shows a proposal made by Zheng et al (2018). On the horizontal axis are located the challenges in Industry 4.0, which they have defined as smart design, smart manufacturing, smart machining, smart control and smart scheduling, while on the vertical axis are located Industry 4.0 challenges in data detection, collection, analysis and use.

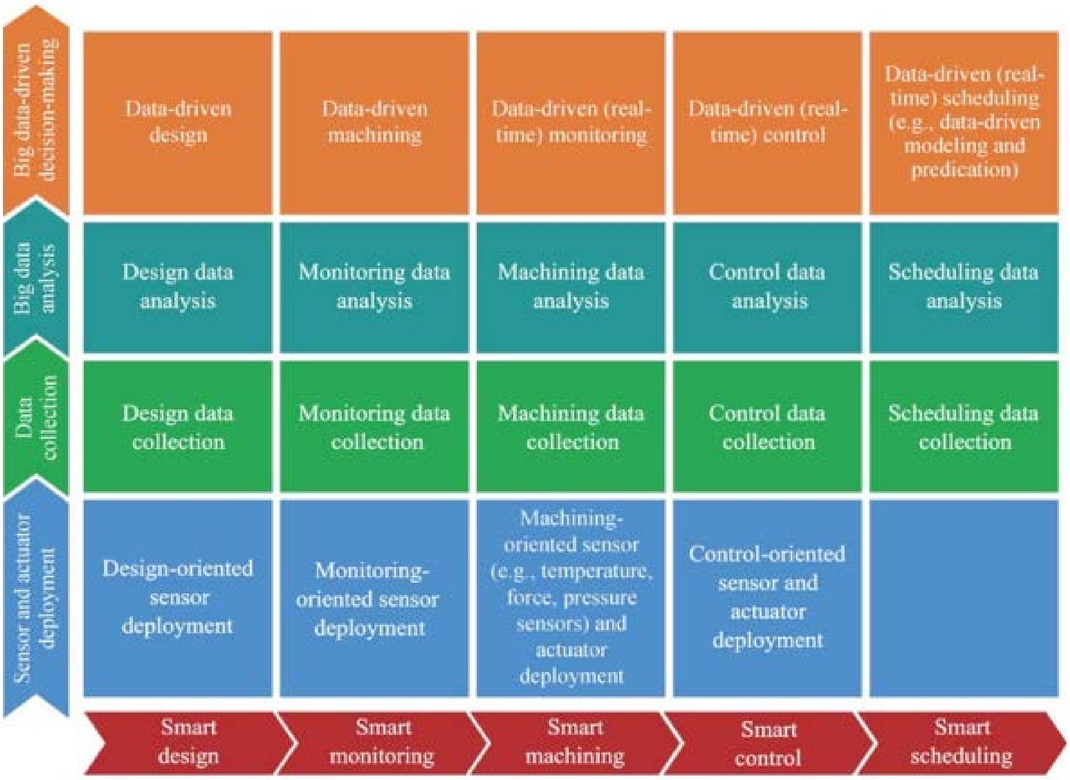

Figure 11. Conceptual framework of I4 smart manufacturing systems (Zheng et al, 2018).

As can be seen in the first column from Figure 11, traditional design as it is known will also evolve within Industry 4.0 thanks to the emergence of new technologies, thus transforming into a smart design process, that will allow companies to adapt to the current large amount of demand and satisfy the individualized needs of the costumers, thus positioning themselves competitively in the market (Onyeme et Liyanage, 2021; Zheng et al, 2018).

This is not something new. Since the appearance of the industrial revolutions, the industrial design process within the industry has evolved with them, as shown in Figure 12. During the first industrial revolution and the apparance of steam power, the design and manufacturing process tried to imitate craftsmanship, seeking to increase functionality and volume of production through the mechanization of processes. With the arrival of mass production thanks to electrification and assembly lines brought by the second industrial revolution, products could begin to be designed to have greater functionality and to be manufactured in larger volumes than before. The emergence of assembly lines also produced a shift in the approach of industrial designers, focusing more on the ease of assembly, and thus producing standardized and interchangeable parts, in addition to seeking an increase in the speed of production and decrease in costs. In the third industrial revolution, the advent on CAD and automation of processes made the design process more digitized, thus allowing to validate designs through simulation models and optimize the initial proposals. Moreover, thanks to this digitization, design and manufacturing processes were networked, thus permitting to share data between processes. As a result of all this, it was possible to increase the quality of the final product more, additionally to reducing costs and lead-time. Lastly, the fourth industrial revolution and the advent of its technologies are blurring the line between the physical and virtual world, allowing to carry out smart and optimized design and manufacturing processes, along with getting a more customized product both for consumers and the company, thanks to data-driven decision making (Jiao et al, 2021).

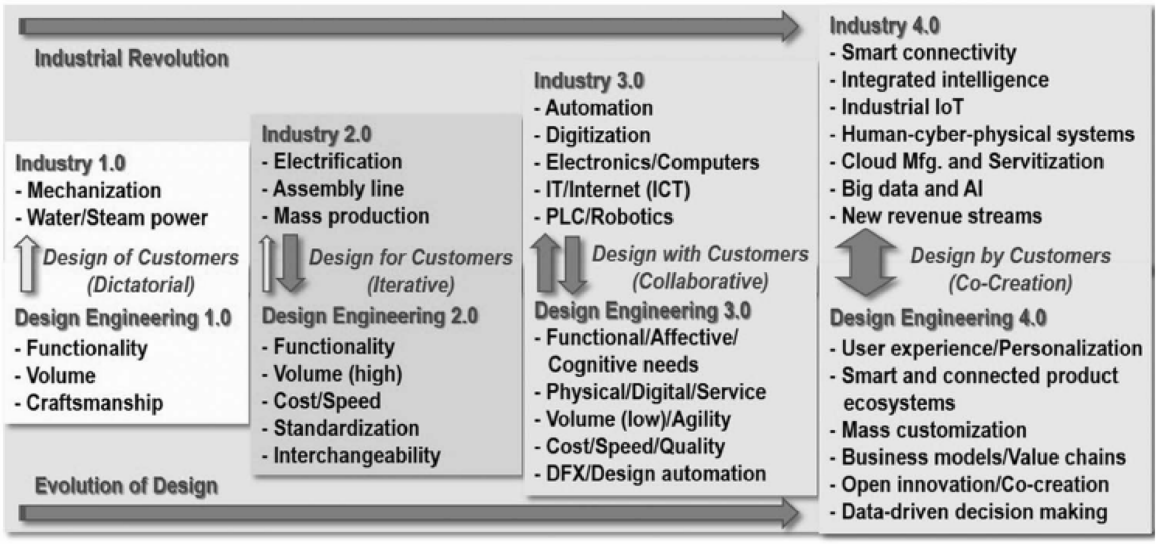

Figure 12. Evolution of Industrial Design through industrial revolutions (Jiao et al, 2021).

These new ways of carrying out the design process brought by Industry 4.0 are still in a process of constant adaptation since, apart from the benefits it would bring, the implementation of the technologies brought by the fourth industrial revolution and the digitization of processes will become crucial for companies to stay competitive in the market. Within the current methodologies of industrial product design and development, as previously seen, the Design for Manufacturing approach is already an useful way of improve product competitiveness, considering design goals and product restraints from a early stage of the design process in order to get the best design for the ease of manufacture (Kerbrat et al, 2011). The merge of this methodology with the smart design process brought by industry 4.0 can boost the benefits provided by each of them. These new technologies used in smart design may cause changes in the way of using DFM in the product design process, being able to use them as a tool to help designers when applying the methodology, taking the application benefits to a whole new level. Aside from this, given that industry and processes are increasingly becoming more digitalized, consideration of I4 technologies within DFM methodology will become necessary in the future since, as said before, manufacturing processes will begin to work gradually more with them.

4.1. Implementation challenges

Before implementing the use of smart technologies into current DFM methodology, there are some challenges that companies and/or designers must comply for its correct implementation and get the most out of it. According to Schuh et al (2016), these requirements would be the following:

- Orientation: Possibilities of the business model are larger by a multiple for a connected, smart factory, due to manufacture processes being connected. For this reason, it is needed to adapt the current methodology and procedure in this context of I4, taking into account the use of intelligent technologies and the constant connection between humans, devices and sensors.

- Data: The second requirement would be generation and analysis of high-resolution data, since, although there are diverse milestone plans, design data, value stream mapping, there is still no high-resolution data. Its collection, analysis and storage will allow not only to take information from existing processes but also to generate new information through the processes carried out over time.

- Interaction: There must be a constant connection with the process and product. In this way, it will be possible to know in what state the product is in any phase of the design process, allowing to intervene and interact with it at any time and from anywhere.

- Resources: Designers and companies must have the necessary resources and tools in order to achieve convergence of physical and virtual world, and thus being able to work in an intelligent-interconnected factory.

4.2. Conceptual framework

Since requirements in the context of traditional design process are fundamentally different from developing products for Industry 4.0, there is a need for a holistic approach for its integration of and making an efficient use of the smart technologies within the design process, taking into account the different characteristics of the different devices and considering their different functions.

In order to find different ways to integrate the new emerging technologies brought by the fourth industrial revolution into the context of product design and the DFM methodology, it is needed to answer a set of questions. As in the previous section, it has been decided to pursue and adapt the framework proposed by Schuh et al (2016), dividing those questions into two dimensions:

Dimension I: Perspectives for industrial design and DFM-approaches.

- Product: How should be designed the product in the context of Industry 4.0?
- Process: How has the manufacturing process evolved in the context of Industry 4.0?

Dimension II: Challenges in product development and manufacturing in the context of Industry 4.0.

- Orientation: How should product design and development be orientated in the context of Industry 4.0?
- Data: Which data is available and which role does it play?
- Interaction: How is an Industry 4.0-specific communication and collaboration defined?
- Resources: Which resources, methods and tools are available in this context?

Once the dimensions and research questions have been defined, the different sub-dimensions between them must be interconnected, thus covering all the possibilities of integration of the technologies from I4 within the DFM methodology. As shown in Figure 13, it results on a framework with eight different fields, which are (Schuh et al, 2016):

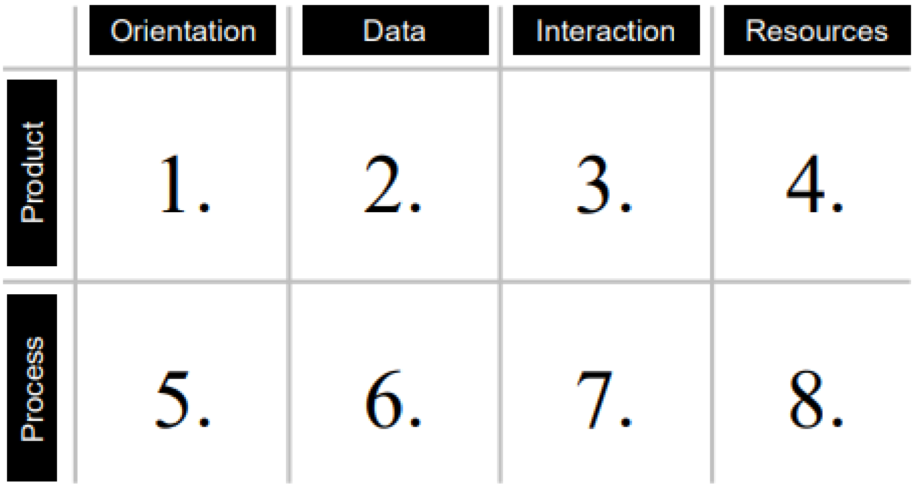

Figure 13. Conceptual framework of DFM for I4 (Schuh et al, 2016).

1. Product orientation: Specific design guidelines in an Industry 4.0 context.
2. Product data: Product optimization via usage of high-resolution data.
3. Product interaction: Constant connection and communication with the product.
4. Product resources: Usage of reliable data to achieve efficient products.
5. Process orientation: Process innovation in an Industry 4.0 context.
6. Process data: Process optimization via usage of high-resolution data.

7. Process interaction: Constant connection and communication with the process.
8. Process resources: Integration of new technologies into processes.

4.3. Integration of the enabling technologies from I4 within the DFM process

Each technology would be applied in different parts of the design process, given its different characteristics. These implementation locations will be explained from the graph shown in Figure 14:

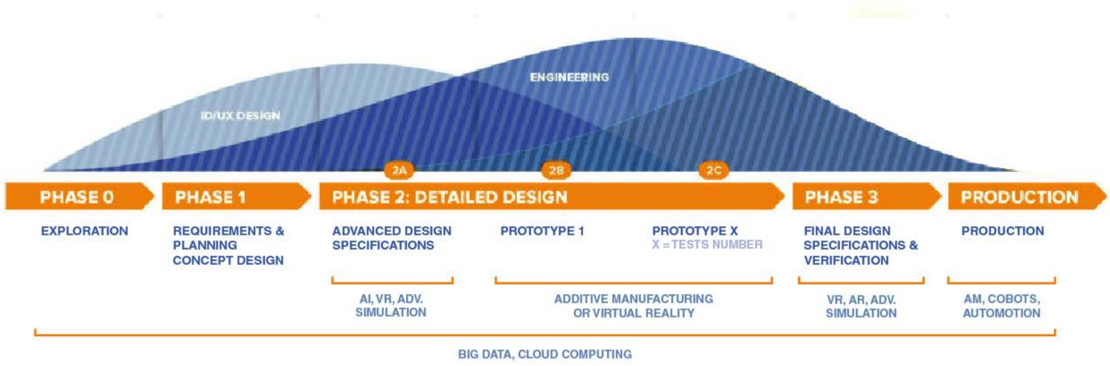

Figure 14. Use of the smart technologies within the DFM process. Adapted from https://www.simplexitypd.com/resources/product-development-process/

Throughout the process, Big Data and Cloud Computing would be always present. The first allows us to collect, analyze, filter and store information while the second allows us to access the information collected and the necessary resources, in addition to being a support for other technologies used. The information available thanks to Big Data could be about market trends, consumer needs, information from the product development sector (phase 0), requirements or information about the behavior and operation of materials in specific situations, as well as manufacture processes (phase 1). During phases 2-3 and during production, the information produced by the process and procedures followed (its progress, successes, failures, etc.) would be collected to store it and serve as a utility for future processes. As said before, the technology that would allow to access all of this information, as well as act as support for the software of other technologies, is Cloud Computing.

In phase 2, once it is had the design concept, with its corresponding design, manufacturing and material requirements, Artificial Intelligence can be a very useful tool so that, through these requirements, it can be reached a more advanced design. Once these are reached, a Digital Twin of the best possible designs considered by the designers, as simple or as complex as it is needed, can be created, so tests on manufacturing, behavior, dimensions, ergonomics, etc. can be done through Virtual Reality and advanced simulation processes, to be able to see the possible results in a closer way. It can also be performed easy and fast prototyping using Additive Manufacturing, and thus checking the results in a physical and tangible way. Once the final design is chosen, it can be verified in phase 3 via usage of the same tools.

4.4. Benefits of incorporation of I4 technologies into DFM

As has been seen on the first sections, the use of DFM could bring various benefits. Therefore, incorporating the technologies from the Industry 4.0 in this methodology would bring added benefits to those previously achieved, providing a step-change in productivity, efficiency, experience, and flexibility (Jain, 2019).

The main benefits to highlight are cost and lead time reduction. New technologies are powerful tools which could be very helpful with the work of designers. Those smart electronics, such as Virtual Reality and advanced process simulation, would help on the decision making in the design stage, allowing designers to interact with the designed object and process simulations and see a replica of the events that would occur in the physical world, thus seeing what changes or process options are best, or, as may be the case with Artificial Intelligence use, it can directly give the designer the best options to follow in terms of design and ease of manufacture according to the objectives of the product, allowing to achieve the best optimized final design in a faster way, thus reducing lead time.

Thanks to the obtaining of the best optimized final design, costs are also reduced, thanks to the simplification of the product and the process-material selection becomes more efficient. Moreover, getting help from those smart technologies would reduce errors rate, given its ability to detect problems earlier and resolve them more quickly, thus reducing the possibility of having to do reworks, consequently saving money and avoiding waste, reaching a better use of available resources. Process efficiency, flexibility and productivity will also be positively affected, thanks to the constant interconnection between devices and between devices and humans, continuous analysis of data and self-correction by these smart technologies. The product obtained will also be, for the reasons previously explained, of a higher quality, which, together with cost reduction and lead time, will generate greater satisfaction in the customer, since they will be obtaining a higher quality product at a lower price and in a faster way. This will allow to companies or design teams to position themselves more competitively in the market, thanks to obtaining a differentiated product, as well as increasing productivity and profitability, and gaining new costumers due to satisfaction.

Other benefit to bear in mind is related to the use of Additive Manufacturing technologies, which, in some cases, allows designers to avoid from differing greatly from their initial concept design in order to achieve a design for the ease of manufacture, since thanks to AM it is possible to achieve complete or parts final design that would be impossible or very difficult and expensive in money and time to obtain by traditional manufacturing methods.

<table>
<tr><td rowspan="7">Benefits of incorporation of I4 technologies within DFM</td><td rowspan="5">Cost and lead time reduction</td><td>Help from smart technologies in decision making</td></tr>
<tr><td>Efficient process-material selection</td></tr>
<tr><td>Product simplification</td></tr>
<tr><td>Achievement of the best optimized final design according to requirements</td></tr>
<tr><td>Error rate reduction</td></tr>
<tr><td rowspan="2">Sustainability</td><td>Optimization of resource usage</td></tr>
<tr><td>Waste reduction</td></tr>
</table>

	Process efficiency, flexibility, and productivity	Constant interconnection
		Continuous analysis of data
		Self-correction
	Less design restrictions	Ability to make parts that cannot be made by traditional manufacturing
	Customer satisfaction	Increase of product quality
		Cost and lead-time reduction
	Greater competitiveness in the market	Increase of costumers
		Increase of productivity
		Differentiated product

Table 7. Benefits of incorporation of I4 technologies within DFM.

4.5. Barriers of incorporation of I4 technologies into DFM

Despite the benefits it could bring, we would also find certain barriers to overcome when incorporating the smart technologies in the Design for Manufacturing methodology, given the fact that both DFM and Industry 4.0 have them separately.

The biggest problem we would encounter is again the human factor. Incorporating these new technologies in the methodology as a tool would change the traditional way of working, changes to which people are usually reluctant. These changes would also imply a need for learning, since currently, most designers do not have the necessary competences for the use of these technologies, which results in additional money and time costs on training courses, despite from the fact that the use of these technologies supposes a continuous learning given its constant evolution. Another important expense to be made would be in the acquisition of these technologies. In order to get the smart devices brought by the fourth industrial revolution, companies or independent designers would have to make substantial investments, which is not known if it will be recovered in the future because the benefit that will be acquired by the use of this technologies is not known with certainty. As being something relatively new, there is still not enough trust on their reliability and stability.

Another barrier to overcome when it comes to technological integration are the storage systems. Due to the constant flow, processing, and storage of data, whether manufacturing processes, materials, design trends, past experiences, better interfaces will be needed in order to withstanding them. This interface, apart from withstand the useful data to apply in the Design for Manufacturing process, will also have to be able to store the different programming languages and methods of operation from the different technologies.

Barriers of incorporation of I4 technologies within DFM	Human resources	Lack of skilled workforce
		Need for new competences
		Need for training courses and continuous learning
	Financial resources	Huge initial investment
		Uncertainty about benefits and profitability
	Technology integration	Need for large amounts of storage
		Lack of trust in the systems
		Lack of trust in reliability and stability
	Resistance to change	Disruption on current jobs
		Reluctant workers

Table 8. Barriers of incorporation of I4 technologies within DFM.

4.6. Examples of application

4.6.1. Big Data in DFM

When DFM methodology is followed, it must be taken into account the fact that the data generated by design or manufacturing processes, from material selection, etc, can be used to improve the efficiency of those processes, as for make it easier to take some decisions.

Data would be collected and analysed at every stage of the design and manufacturing processes, as from the costumer behaviour, with the possibility of being used to improve the design of products and make better choices when it comes to identify customer needs and market trends, choose the manufacturing process, materials to use, or even to help to find the best design changes in order to ease manufacture, identifying patterns and trends, optimizing resources and improving quality control.

4.6.2. Additive Manufacturing in DFM

Via additive manufacturing, rapid prototyping can easily be done for feedback, both from engineers and technicians as well as from designers. This way, the possible need of design changes can be checked, either for functionality or ergonomics, among other reasons. AM can also be used to manufacture final products or in conjunction with other manufacturing processes, and due to its control softwares (eg. *Ultimaker Cura* for FDM, or *Photon Workshop* for SDL) the cost can be easily estimated from early stages when the material or materials have been chosen. This would allow designers not to worry about complexity or expanding their creativity wings, since it is not as limiting as other manufacturing processes, letting to manufacture some parts or complete products that where unthinkable in the past. Moreover, compositions of complex materials can be made, since it is possible to have a different processing of materials in different regions (Campbell et al, 2012; Rosen and Samyeon, 2021).

According to Rosen and Samyeon (2021), the perfect example of the complex geometry that can be achieved thanks to AM is the satellite part with lattice structures shown in Figure 15, done by Adimant for Thales Alenia Space in 2016. This part has reduced dimensions and mass, to be exact, a size of 134x28x500mm and a mass of 1,7kg, which facilitates heath exchange. This small dimensions and reduced mass design, as well as the reticular structure or other complex forms, can not be achieved by conventional manufacturing.

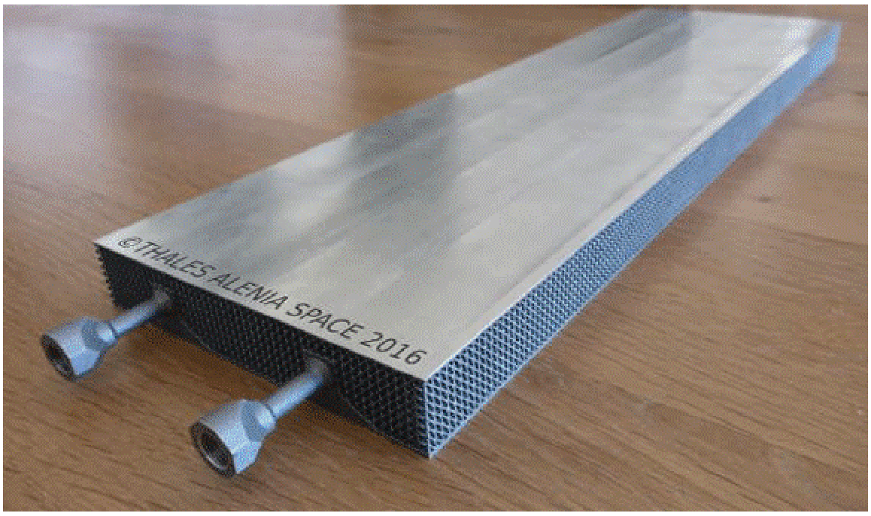

Figure 15. Metal printed satellite component with lattice structure from Thales Alenia Space (Rosen and Samyeon, 2021).

4.6.3. Artificial Intellignce in DFM

The use of Artificial Intelligence within Design for Manufacturing process can be diverse. For example, predictive or generative design can give the most optimal final design considering materials, process of manufacture, time or cost (among other restrictions) given the initial product design, due to all the data collected and transferred to AI. It can also give different options with all that information to help to choose the option that is a better fit. Thanks to this technology, it is not only possible to create new products following materials and manufacturing requirements, but also allows to improve existing ones for the ease of manufacture.

Using AI within design does not intend to replace designers but to optimize its work, reducing workload and increasing productivity. In addition, it bridges gaps between design and manufacturing engineers, given the creation of designs based on its constraints , as well as it allows to create differentiated and optimized designs in a faster and more economical way (CampusMVP, 2021).

In addition, Artificial Intelligence is constantly learning and evolving, not only by the constant flow of information on the network, but also for what it learns through the design, materials and manufacture choices that are made.

Softwares like *Fusion 360* or *Dreamcatcher* allow the designer to obtain different design solutions by determining design goals and constraints. Next off, from Figure 16 to Figure 20, we can see an example extracted from Cohee (2018), where the design of some car pedals with generative design is improved using *Fusion 360*.

First, existing pedals are taken from a automobile with the aim of improving its design. The important geometry from the original design is selected and isolated in order to generate the new designs from them. The corresponding conditions and restrictions apply to each part, as well as the material of which they are conformed. Once this is finished, you can start generating the designs that suit those requirements. In the case of the example, sixteen different designs were generated. From here, according to Cohee (2018), it is up to the designer to choose the option that best fits their objectives. To help in this decision, some graphs are available to be able to sort, view and compare information about the results. In addition, results can be controlled via filters, that allow to control the range of the objectives, based on this case on volume, weight, maximum displacement, maximum von Mises stress and maximum factor of safety, thus eliminating options equal to or worse in characteristics than the original design. The final result managed to be a 15% lighter, stiffer and stronger than the original, in addition to reducing the number of parts by 86.

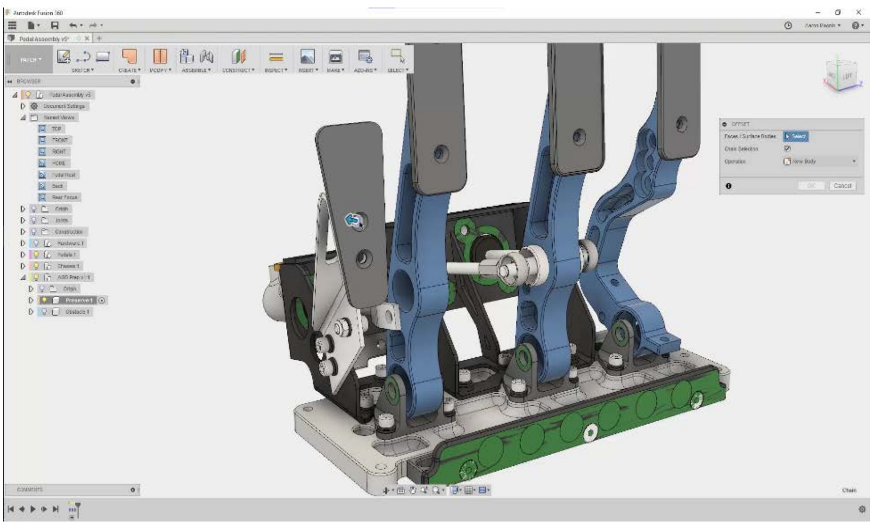

Figure 16. Initial design (Cohee, 2018).

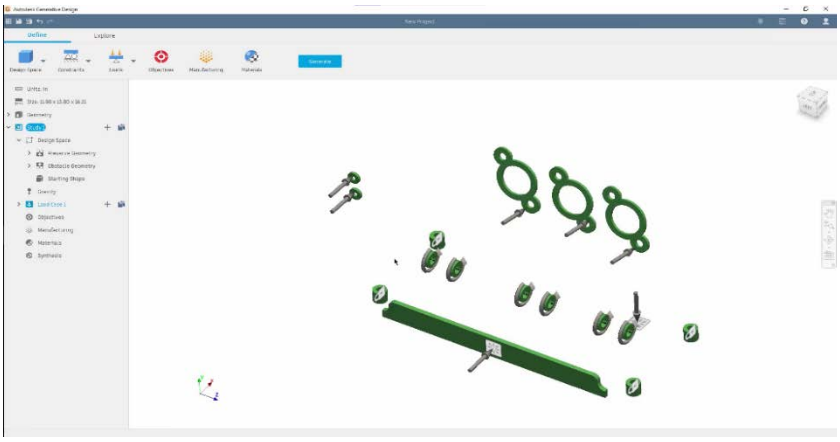

Figure 17. Important original geometry preserved with its conditions and constraints (Cohee, 2018).

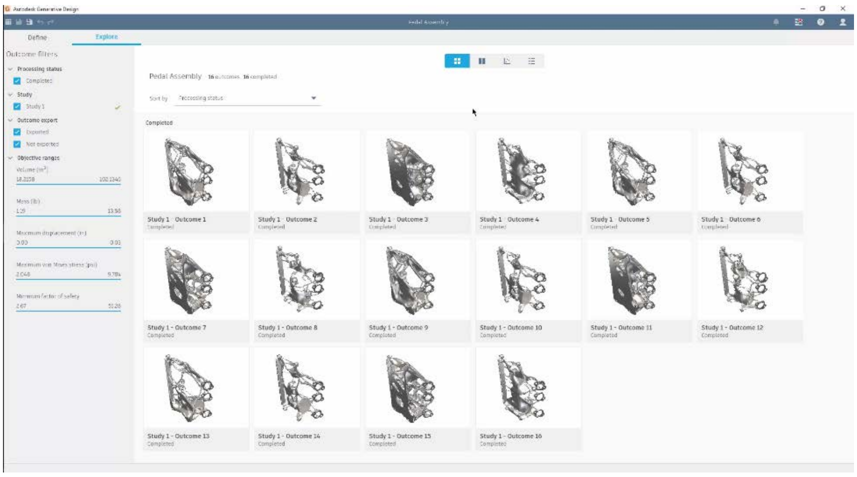

Figure 18. Generated solutions (Cohee, 2018).

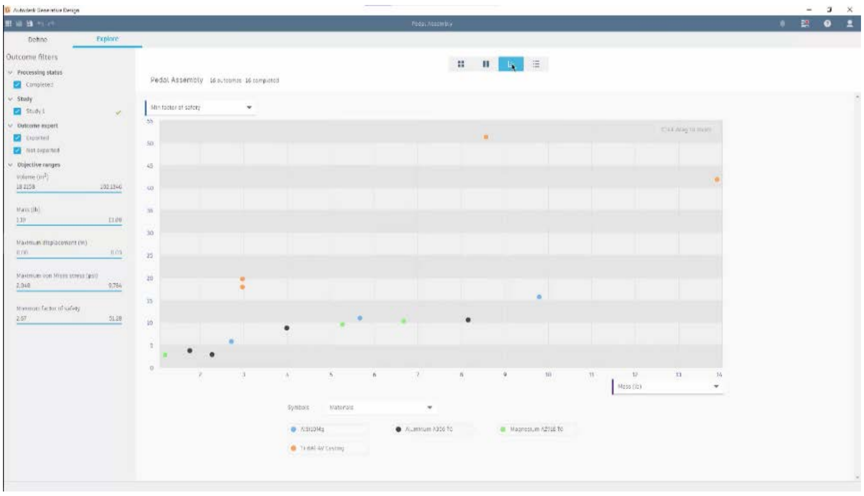

Figure 19. Outcome filters to sort view and compare solutions (Cohee, 2018).

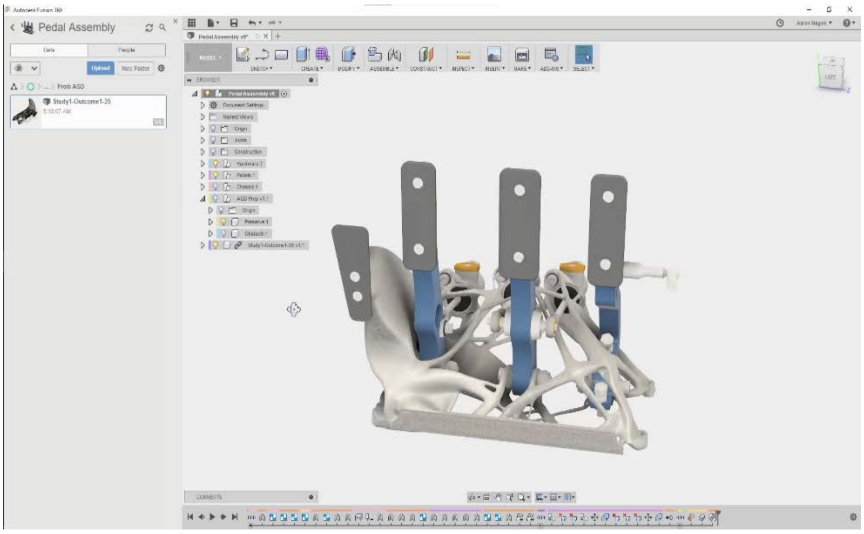

Figure 20. Final generated design chosen (Cohee, 2018).

4.6.4. Virtual Reality in DFM

When it comes to Virtual Reality, people think more about videogames and entertainment than Industry, but truth is that it has very useful applications in this sector.

Applying VR technologies in DFM allows designers to gain a sense of spatial depth and volume by viewing the 3D model of the product immersively (Liu, 2020), giving designers more consciousness about its dimensions, ergonomics, etc., in addition to being able to directly interact with the design and make changes. This gives a greater awareness of the product and allows to detect failures in an easier and faster way (Invelon, 2019). It can also help for advanced simulation programs, where it could be used to see the behaviour of the design of the product before different analyses considered of importance to demonstrate its correct performance or view the production process as if they were performed in physical reality, being able to see the different products resulting from different manufacturing processes and use of different materials, in order to choose the option that best suits. Thanks to all this, it would not be necessary in some cases to have to make physical prototypes, thus saving money and time, since through Virtual Reality you could obtain all the necessary information about the designed product.

To represent this, it will be presented the case of the application of VR within the automotive sector. In order to test automobile performance virtually, three modules are required: input module, virtual dynamic control module and output module, depicted in Figure 19. Firstly, in the input module, the automobile, scene and other needed parts are imported from 3D files or proportionally constructed via the VR software. Once shapes and materials are completely defined, the dynamic control module begins, where industrial designers and manufacturers give to the virtual scene interactive operational instructions in order to experience and evaluate its performance through sensors.

Once the evaluation is completed, parameters are modified and this method is repeated until the industrial designer or manufacturer deems it necessary, testing and modifiying parameters in order to achieve the best performance of the automobile designed (Xu and Lv, 2011).

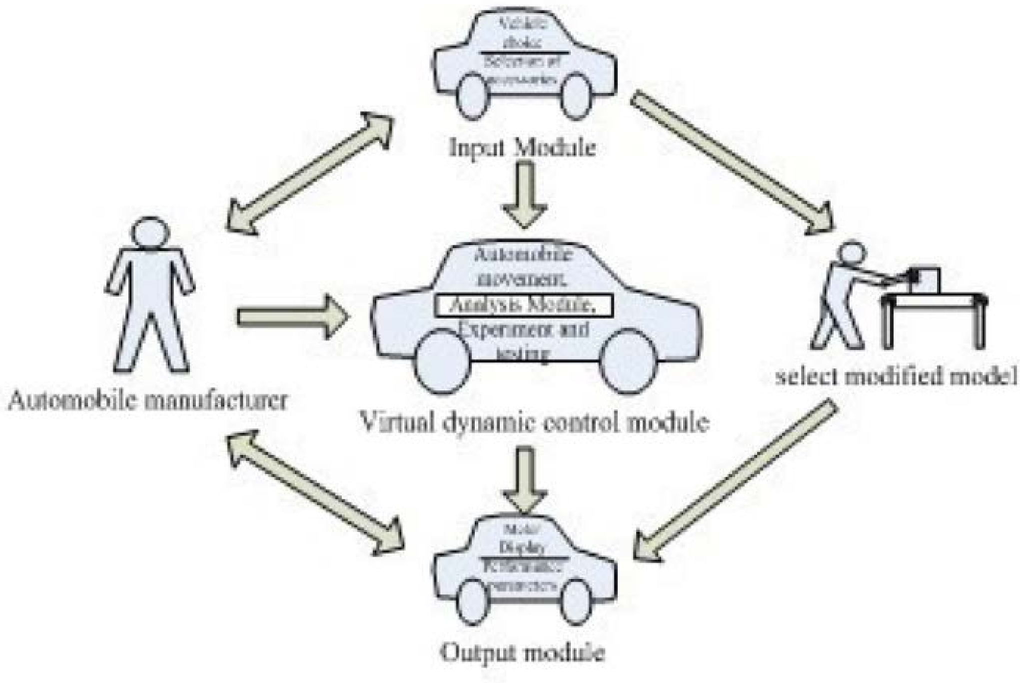

Figure 21. Virtual automobile performance testing system chart (Xu and Lv, 2011).

4.7. Closing remarks

Due to the technological changes and digital transformation brought by Industry 4.0, current industrial design processes must evolve and adapt to these new technologies on the rise in order to achieve benefits both at the process level and at a competitive level in the market. This fourth section has been focused on the impact of this fourth industrial revolution within the Design for Manufacturing methodology.

To begin to develop a new work methodology, it is necessary to establish implementation challenges as well as a conceptual framework. Although it has been followed a proposed line of study to explore about them, that does not imply that this is the only possible one since currently there are no fully defined guidelines, and it is up to the company or design team to consider which one to follow. What is certain is that, as said before, in order to maintain competitiveness in the future market, in addition to achieving a boost in what this methodology contributes to industrial design, Design for Manufacturing will have to embrace the changes brought by the fourth industrial revolution, thus becoming an intelligent design process. Furthermore, thanks to this analysis it has been observed that some of the barriers of DFM can be solved thanks to the introduction of new technologies, and therefore making its implementation easier or improving it in the event that it was already implemented. As has been seen, this new machinery would accompany the designer and the product throughout the design process, making it easier to design for the ease of manufacture as well as adapt to the requirements of the product owing to technologies such as Artificial Intelligence. It will also make the design and manufacturing process interactive and immersive thanks to Virtual Reality, not only allowing the designer to easily work on them, as well as interacting with the it as if it were in real life, but it could even eliminate the need to make physical prototypes since thanks to this technology used for advanced simulation processes it will allow to obtain all the necessary information to know if the product meets all the requirements. Finally, it would eliminate restrictions over the design form thanks to Additive Manufacturing, technology that allows parts or complete products to be made with shapes and sizes that would be impossible or very difficult to perform through traditional manufacturing. It can also be used to obtain physical prototypes of the product in a quick and simple way.

The use of Industry 4.0 enabling technologies would not only help in the design process, but also to control and monitor the manufacturing process as well as its arrival to the consumer, thus allowing the industrial designer to attend the evolution of the product process from its conception to its delivery to the consumer, thanks to the constant interconnection between devices, humans and sensors. In addition to this, the data of the production process are continuously recorded and stored, thus allowing to optimize future processes based on the results of previous processes.

5. CONCLUSIONS AND FUTURE LINES

The realization of this study has been a challenge, given the various lines of work and research within Industry 4.0. To this, we must add the existence of areas that are not yet fully defined, since it is a field that is constantly evolving and adapting.

It has also been encountered the problem that no documents have been found dealing with Design for Manufacturing in this fourth industrial revolution, so the development of the fourth chapter of the work has been based on convergence, adaptation and development from documents that dealt with manufacturing or design within Industry 4.0.

As explained in the introduction, it has been decided to deal first with the key concepts: Industrial Design and Product Development, Design for Manufacturing, and Industry 4.0, all in order to give a greater and better understanding of this document, as well as to introduce in context and help the development of its objectives. This objective was to explore how the Design for Manufacturing methodology may be affected by the use of Industry 4.0 technologies. It begins by explaining the evolution of design with the industrial revolutions to introduce this paradigm, followed by a study of the implementation requirements and the framework of a line of study proposed by Schuh et al (2016).

Once the study was completed, the benefits and barriers that its implementation would entail began to be raised, for which the barriers and benefits of Design for Manufacturing and Industry 4.0 have been compared separately. After this, it is concluded and reaffirmed that the use of the technologies of this fourth industrial revolution in this methodology results in a boost of the benefits of each of them separately, since both have similar benefits. It should also be noted that, although there are certain implementation barriers, some of the benefits of Industry 4.0 override the implementation barriers of Design for Manufacturing, reducing them when they merge only to those of I4. Finally, examples of some of the technologies that can be used are given, talking about their role within the Design for Manufacturing methodology and giving practical examples of their use within this area, in addition to talking about the part of the design process where they could be implemented.

Within my search for information about the implementation of Industry 4.0 technologies in industrial product design, I have come across a proposal that today may sound unusual, but that may be interesting as a future area of research.

This future line has to do with Augmented Reality and the value it can bring to the final product. According to Mauriello (2022), author of the video through which I was made aware of this innovative proposal, “Augmented Reality and the metaverse is the next logical step in digital interaction and will inform several industrial design and product design trends for years to come, offering unprecedented functional utility and new avenues for self-expression.” As seen in the previous chapters, products are becoming increasingly personalized and consumer oriented. Via AR, this customization could be achieved quickly and easily, being also able to break the barriers imposed on us by the physical world to be able to obtain it through the digital objects. By projecting images of virtual objects or textures onto physical objects, value could be added to the product through the addition of materials, shapes and components that would be unthinkable in a physical way. In addition, it is possible to get unique and interchangeable objects without having to go through all the expenses of money and materials, as being able of avoiding the generation of waste since they are virtual objects.

To conclude, I wanted to talk about the main implementation barrier that we find in all sections: people and knowledge. In order to implement the advances brought in Industry 4.0, I think the change should start with teaching. Within the engineering sector, I have met many students who do not know what Industry 4.0 is, which seems to me a mistake since it is what the industries are heading towards in the future. Whether it is because of a lack of this content in the syllabuses they address or because students do not pay enough attention, I think we must go to what I think is the main root; an outdated education. In the current educational system, the same syllabus is often given for years and years. This seems to me a mistake, especially in the engineering sector (which is where I have lived the experience), since society, knowledge and technologies are constantly evolving, and therefore the contents taught should evolve with them. Especially in this context of Industry

4.0, in which we are in rapid and continuous progress, I see it necessary to implement this more in the contents taught (though without neglecting the traditional methods), so that students gain awareness about new technologies and everything that can be done with them, and so in the future they know better to face them and help progress.

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