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Exploring Augmented and Data-Driven Digital Modeling Tools in Product Design and Engineering

Explorando Ferramentas de Modelação Digital, Aumentada e Orientada por Dados em Engenharia e Design de Produto

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Modeling Tools in Product Design and Engineering**

Dissertação apresentada à Universidade de Aveiro para cumprimento dos
requisitos necessários à obtenção do grau de Mestre em Engenharia e Design
de Produto, realizada sob a orientação científica do Doutor João Nunes
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acknowledgements   To my family and friends.

palavras-chave   Indústria 4.0, Realidade Aumentada, Design Generativo, Design Cognitivo.

resumo   As ferramentas são indispensáveis para toda a prática diligente profissional. Novos conceitos e possibilidades de mudança de paradigma estão a surgir com os recentes progressos tecnológicos a nível computacional nas ferramentas digitais. Contudo, novas ferramentas originadas sobre conceitos-chave como "Big Data", "Acessibilidade" e "Design Algorítmico" estão a mudar de forma fundamental o contributo e posição do Engenheiro e Designer de Produto.

Esta dissertação, após uma primeira introdução contextual, começa por extrair três conceitos-eixo duma análise ao Estado da Arte actual em Engenharia e Design de Produto. Em cada um desses conceitos explora-se os novos conceitos emergentes mais relevantes e paradigmáticos, que então são comparados e posicionados no círculo de Gestão de Ciclo de Vida de Produto, apontando aí potenciais riscos e falhas que possam ser explorados em experiências.

As experiências empíricas têm duas índoles: a primeira de projetos e casos de estudo de arquitetura e planeamento urbanístico — experiência em contexto de trabalho do aluno —, que serviu de pretexto e inspiração para as experiências relacionadas com Engenharia e Design de Produto. Primeiro com uma série de análises e experiências isoladas, segundo com uma formulação hipotética com o compêndio dessas experiências e, finalmente, com uma secção de reflexão que culmina numa série de riscos e mudanças induzidas do trabalho anterior.

A urgência em refletir sobre o que irá alterar nesse papel e posição, que género de reformulações éticas e/ou conceptuais deverão existir para que a profissão mantenha a sua integridade intelectual e, em última instância, sobreviva, são bastante evidentes.

keywords   Industry 4.0, Augmented Reality, Generative Design, Cognitive Design.

abstract   Tools are indispensable for all diligent professional practice. New concepts and possibilities for paradigm shifting are emerging with recent computational technological developments in digital tools. However, new tools from key concepts such as "Big-Data", "Accessibility" and "Algorithmic Design" are fundamentally changing the input and position of the Product Engineer and Designer.

After the context introduction, this dissertation document starts by extracting three pivotal criteria from the Product Design Engineering's State of the Art analysis. In each one of those criteria the new emergent, more relevant and paradigmatic concepts are explored and later on are positioned and compared within the Product Lifecycle Management wheel scheme, where the potential risks and gaps are pointed to be explored in the experience part.

There are two types of empirical experiences: the first being of case studies from Architecture and Urban Planning — from the student's professional experience —, that served as a pretext and inspiration for the experiments directly made for Product Design Engineering. First with a set of isolated explorations and analysis, second with a hypothetical experience derived from the latter and, finally, a deliberative section that culminate in a listing of risks and changes concluded from all the previous work.

The urgency to reflect on what will change in that role and position, what kind of ethical and/or conceptual reformulations should exist for the profession to maintain its intellectual integrity and, ultimately, to survive, are of the utmost evidence.

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List of Acronyms

3DML: 3D Machine Learning
AE: Autoencoder
AEC: Architecture, Engineering and Construction
AMC: American Motors Corporation
API: Application Programming Interface
AR: Augmented Reality
Arch&Urb: Architecture and Urban Planning
BIM: Building Information Modeling
BLM: Building Lifecycle Management
CAD: Computer-Aided Design
CAE: Computer-Aided Engineering
CCT: Cognitive Computing Tools
CNN: Convolutional Neural Networks
CRM: Customer Relationship Management
CS: Computer Science
CV: Computer Vision
DD: Data-driven
DL: Deep Learning
DT: Digital Twin
ERP: Enterprise Resources Planning
FL: Fuzzy Logic
GAN: Generative Adversarial Networks
GDL: Geometric Deep Learning
GH: Grasshopper
I4.0: Industry 4.0
IoT: Internet of Things
IR: Image Recognition
IT: Information Technology
LIST: Luxembourg Institute of Science and
Technology
ML: Machine Learning
NN: Neural Networks
OSM: Open Street Map
PDC: Product Design Cycles
PDE: Engineering and Product Design
PDE: Product Design Engineering
PDEng: Product Design Engineer
PLM: Product Lifecycle Management
SCM: Supply Chain Management
VR: Virtual Reality

CHAPTER I . Preamble

1.1 Introduction

"Waste is hidden. Do not hide it. Make problems visible" (Ohno, 1988).

Everything changes at an increasingly faster rate. Similarly, it is increasingly difficult to keep up with all of that. What is true today, tomorrow it is not. Today is the information age and era, where every decision-making process is increasingly more based on extensive datasets and huge flows of information *(Ng, 2019)*.

The Information Age (also designated as the Computer Age, Digital Age or New Media Age) is a period historically situated in the 20th century and with its turn point in the introduction of transistor technology *(Figure 1)*. Its introduction rivaled against the tube and led to the shift from the Industrial Revolution to the industry based in Information Technology (IT). It precedes all the ongoing shifts that are taking place now.

Product Design Engineering (PDE) is a multidisciplinary practice that is now intrinsically connected and dependent to the digital technology that the Information Age brought. Is upon that premise that this document's discourse is built: with the crossing of the technological environment peculiarities — the rate and severity of "changing things" and how unpredictable they are —, and the complexity of PDE — its work range — is a combination that inescapably leads to emergent issues and risks.

Due to the PDE's complexity and to the current state of things, the Design part in the discipline suffers from some issues: specially identity ones. That is quite evident with the core-philosophy in the higher education systems that still prevail today *(Gray, 2011)*. That issue dilutes in all Design practice (and consequently PDE) to its most elementary level.

- Nobody can give a definition of its scope;
- There are regular improper appropriations from the term, foisted in decontextualized context;

Pondering about the *status quo* and try to infer and predict the direction of the general direction of the undergoing changes is the main goal of this document. To ultimately impact directly and indirectly people, groups and institutions that work and are influenced by Product Design Engineering.

Figure 1 First Transistor 1947 (Source: Wikiwand)

To help explain most of that "inspirational" reliance from the author of this document, some quick background disclosure must be made — specially the one as of the time of this document's creation.

The first aspect that molded the author's views was the multidisciplinary approach to the Design's practice: in a first stance at the academic level — with early experience from a wide variety and richness of Design applications —, and in a second one, the professional experience: from various backgrounds from architecture to engineering. From that diversification, some personal statements started to appear:

- Design does not live by itself; it's hybrid: which means it only makes sense contributing to some other scientific field, as its influences are also very diverse (social, psychological, engineering fields);
- Design is not consensual. Because of that, its role and degree of indirect influence to other disciplines its not yet clear (nor the benefits of trying to make it more consensual;
- The Design terminology is endemically, culturally and subjectively defined, adapted and interpreted. It has a different meaning for different people.

That exercise was the first decree. The second was the circumstances: the student's acceptance for a work Investigation and Research contract at Luxembourg Institute of Science and Technology (LIST) for five months *(Figure 2)*. The experience helped to raise awareness from unheard concepts and some that were lacking practical experience — in a more architectural and urban planning level. That experience ultimately led to the technical inspiration for the project part.

Figure 2 LIST Belval (Source: LIST)

With that in mind, the necessity of a less cynical Design practice *(Providência, 2012)* and a more scientific and assertive methodology for Design *(Simon, 1998)* is assuredly needed. The pivotal point of reflection and exploration will be the way the Product Design Engineer (PDEng) and its relation with the tools implied in the practice. How do they influence the PDE practice? How biased is their influence? What are the new trends? Is the PDEng in risk?

1.1.1 Objectives, Scope & Aim

The main objective of this dissertation is to identify and evaluate the current, conventional and emerging tools and frameworks for Product Design Engineering (PDE), along with empirical verifications through experimentation. The main actions are:

- Identify the new concepts and current tools applied in Product Design Engineering;
- Explore and identify the sub-concepts categories and their correspondent tools and frameworks;
- Empirical experiments and exploration with a selected example cases;
- Schematics and representation of future challenges of the Product Design Engineer (PDEng) through its risks and changes.

From this point, some general overview and scope can already be drawn. From outlining this general key concepts, some questions appeared before anything:

- What is the most prominent type of tools in PDE practice? How reliant is PDE with those tools?
- At which pace are the new emerging technologies affecting tools and consequently the PDE?
- What are those emerging tools and frameworks? At which extent will they change the PDEng role? What can he do to retain its "professional integrity"?

Specially with the last bullet point, the main question is: what kind of change — because it will exist — it is required as of now to the PDEng so it can preserve its professional integrity? The "professional integrity" refers itself to the latent risk of displacement and obsolescence of human resources when their professional scope is substituted (rather automatized) by the implementation of those new tools. The point being that the conditions, implications is becoming increasingly faster and more volatile. Specially for digital tools and frameworks.

To close this chapter with the fundamental question: how is the PDEng workflow nowadays and the upcoming changes will make it obsolete in the way it is practiced right now?

1.1.2 Document Structure

In a general overview of the procedures for this document, they'll be displaced as following (with a brief description for each one).

Past the first half of the first chapter with the introductory notes, some contextual introduction to the thematic of this document shall be made: there it will be made an overall historical retrospective about the usage and implementation of tools.
The second chapter will be exclusively dedicated to the identification, categorization and comparison of the most prevalent examples of tools' applications in Product Design Engineering (PDE). First, with introducing the reference methodology — Product Lifecycle Management in this case —, with the introduction of the key term where all the research revolves. Next, the State of the Art qualitative analysis to the current most prominent tools in PDE. From the "raw" research of use cases, some core categorizations was drawn — groups and sub-groups —, that will help build the mental model and later comparison and reflection of the examples.

Chapter three and four will introduce the empirical experiments two main sources. The first one being the one that resulted from the student's internship work. The inclusion of this experience is justified for it being relatable with the PDE discipline. In practice, it served as the indirect foundation for the next part: empirical experiments applied to PDE. Here, all the previous knowledge and conclusions shall be put into test, in order to gain a resilient conclusion for the last chapter.

The fifth and last chapter shall be a symposium of changes and risks for the Product Design Engineer role and profession in the upcoming years in an attempt of establishing a framework of action and verification that will help predict those changes and maintain its professional integrity and position.

1.2 Tools

1.2.1 Augmented Human Creation

"For product designers, tools and techniques are essential in driving the design cycle" (Lutters et al., 2014).

The relationship of the human with tools are inherent and self-proclaimed. Being the triad of humans, tools and creation so compelling to PDE, their analysis is decisive for its the good practice.

One thing only has always been indissociable and omnipresent historically in that relationship: the hand. Indeed as makers and primates, we rely heavily in our hands and gestures in our everyday interactions *(Apple, 2007).* Those who succeed in exploiting that potential are guaranteed to rise above everything else *(Figure 3)*.

The magnifying and enhancing properties of the tools. They augment human capabilities directly into its creations. "Create something bigger than itself". Classify and categorize tools is not an easy task. Although if one focus its range of applicability *(Lutters et al., 2014)*, it can be possible.

Figure 3 iPhone (Source: Apple)

1.2.2 Tools, Etymological Perspective

It could identify tools by its etymological property: its essence. Tools as an indispensable part of human doing, embedded in such manner that become latent in every modern creation. No task is attained without some sort of tool nowadays.

There is also the incremental property of the tools: they do not begin from scratch. They are instead incrementally built one upon the other.

- Tools may not be intuitive: they require a big learning curve;
- Tools may be limited: may not work with everybody;
- Tools may not be effective: may not solve the problem the way it was intended.

The manifest high importance of tools it is easier to verify by a quick historical analysis.

Figure 4 1st Industrial Revolution (Source: Miljan Elcic, Medium)

Figure 5 2nd Industrial Revolution (Source: NCLabs)

Figure 6 3rd Industrial Revolution (Source: Intel)

1.2.3 Tools, Historical Perspective

Historically, the tools' origin can be dated back to the period where humans started using communication (language), resources (agriculture and fire) and, ultimately, (physical hand-made) tools. The latter, along with drawing, became the first evidence of creative-embedded tools. That marks a turning point of a succession of developments that drastically fast-forward evolved to more recent milestone paradigm shifting events: the industrial revolutions.

Industrial Revolutions mark the turning points in the fundamental way modern society and industry works. As of the moment of this document it is considered to be four: the first three already happened or managed to reach their "peaks", and the fourth as the ongoing one.

(1765) 1st Industrial Revolution: mechanization, steam and waterpower. The shift from the agrarian to the urbanized and mechanized way of doing things. The "factory" was born *(Figure 4)*.

(1860) 2nd Industrial Revolution: Mass production and electricity. The acceleration of production, introduction of fossil fuels and the paradigmatic example of Henri Ford's factory *(Figure 5)*.

(1969) 3rd Industrial Revolution: Electronic, IT and automatization. The introduction of electronics, computer and internet, represented by the Intel 4004 in *Figure 6*. It will be briefly covered in the next chapter.

(*Present*) 4th Industrial Revolution: Cyber-physical systems. The aim of exploration of this document. The inter-connectivity of systems and liberalization of processes and tools. Shall be covered throughout the document.

Each one represents a profound societal change that equally influenced the contemporary way of doing things. As such, the introduction of a new paradigm never comes without cautions and risks to avoid — this time being no different.
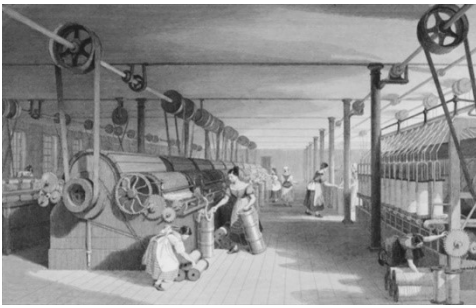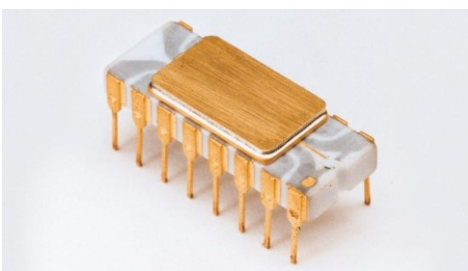
1.3 Digital Tools

1.3.1 The Digital Revolution Predecessor

The Digital Revolution is the paradigm shift represented by the change from a more mechanical and analogue-based electronic technology to an embedded circuit technology. One of the main references for this part is the Eric Lutters' paper "Tools and techniques for product design", 2014.

This period officially begin in the late 1950s up until to the late 1970s — where the proliferation of digital computers usage can still be seen developing today. Technologically, the turning point can be considered the introduction of the modern transistor: — the key artifact for the introduction of integrated circuits chips. Objects and tools such as computers, mobile phones and the internet rely fundamentally in this technology. With this, the introduction of concepts such as the Moore's Law — that states that the number of circuits in a dense integrated circuit will double exponentially every two years *(Martin, 2019)*.

Computer Science and Engineering disciplines along with the electronic devices, computerization and automatization became a fundamental part of the industry and creative areas, including Product Design Engineering (PDE).

Although a designer can use a wide variety and range of tools, including conventional ones *(Lutters et al., 2014)*, today there's a undeniable influence of the digital tools in the overall Product Lifecycle Management (PLM) and Product Design Cycles (PDC). The Product Design Engineer skills require a wide and holistic approach to a multitude of disciplines and actions that integrate both digital and more conventional tools[1].

Despite of this classification being clearly insufficient, it gives an overview about the most common used tools in PDE — corroborating the statement of them being mainly digitally-based. Therefore there are (even more) sensible to the overall change — undergoing right now.

[1] Geometric dimensioning and tolerancing (GD&T).
Quality function deployment (QFD).
Design for manufacturing (DFM)/Design for assembly (DFA).
Value engineering (VE).
Design of experiments (DOE).
Failure mode and effects analysis (DFMEA/PFMEA, etc.).
Finite element analysis (FEA).
Solid modelling.
Simulation techniques.
Computer aided design (CAD)/Computer aided engineering (CAE).
Reliability engineering plans.

1.3.2 Creative and Creation Fields

Product Design Engineering (PDE) holds a very peculiar amalgamation of disciplines: it conjugates artistic creativity and technical engineering skills into the same working environment. The similar disciplines representation could be represented by its "pragmatic dimensionality" *(Figure 7)*:

i. UX/UI;
ii. Product Design (and Engineering);
iii. Interior Design;
iv. Architecture & Urban Planning.

Between each other there is a scalar increment stepping. Beyond that their core epistemology remains untouched though — that amalgamation of the more human and *tecno* part *(Providência, 2012)*. That connection string that draws the contrasting practices together is going to be used later on to borrow empirical experiences and use cases from one discipline to another. Simply put: each one of them contains those two dimensions (creative and creation) and they complement each other. They all are reciprocally relatable and influenceable: both historically and pragmatically.

Whereas the Engineering part in PDE has its role's focus in a much clearer spotlight, there is and there's always been a considerate debate about the pretenses of Design: — its methodologies, scope and body of work *(Simon, 1998)*. That debate goes beyond this document issues' range, although there is one fact that should be reinforced: Design might depend directly on its context, but omnipresently relies on its aesthetic dimension. That is one of the principles that correlates the more human characteristic to it, and imbues PDE with that as well.

The current workflow of PDE is heavily reliant in the digitalization of tools — although not totally. That fact makes PDE highly susceptible to the new set of techniques, tools and frameworks that are currently emerging. For that reason it is urgent to identify what kind of trends, tendencies and tools are surging, which are the new characteristics and new paradigm shifts that the predicted and announced 4th Industrial Revolution will bring. It is also useful to keep in mind the creative side condition ever-latent to PDE: aesthetics sensibility; and that ultimately relates it to other areas.

1. exterior

2. interior

3. product

4. digital

creation/
creative areas
dimensions

urban / arch

design / engineering

1 2 3 4

physical

non-phyical
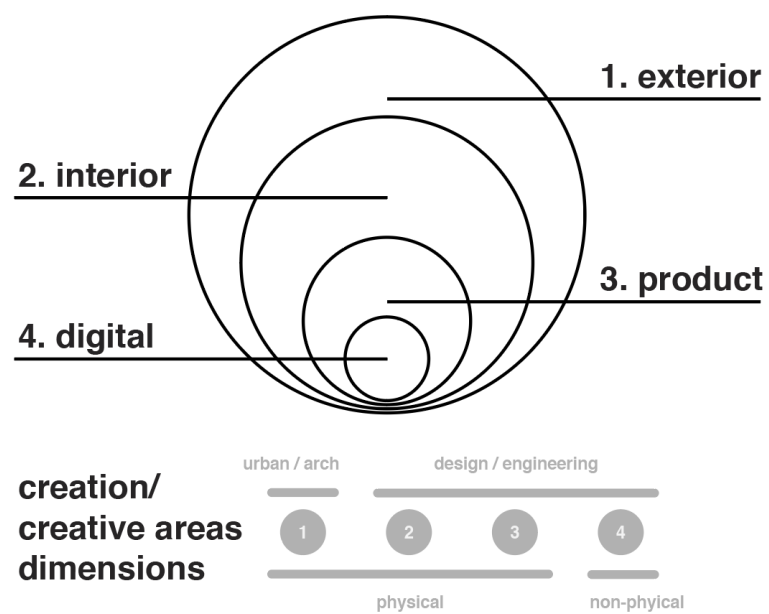
Figure 7 Creation areas inter-dependency scheme

CHAPTER II . State of the Art

2.1 Industry 4.0

"Cognition attempts to make sense of the world: emotion assigns value" (Norman, 1988).

The 4th Industrial Revolution is happening at this very moment of the writing and publication of this document. It succeeds the 3rd Industrial Revolution, the digital one. For the latter there are several sub-fields that emerged meanwhile. The one that relates the most to this document's body of action is the manufacturing, engineering and product design sub-fields. No with many surprises, that sub-field is called Industry 4.0 (I4.0) *(Figure 8).*

"The pivotal core concept and nomenclature from I4.0 is Cyber-Physical Systems (CPS): Cyber-Physical Systems (CPS) are integrations of computation, networking, and physical processes. Embedded computers and networks monitor and control the physical processes, with feedback loops where physical processes affect computations and vice versa" (Asare et al., 2012). Albeit the CPS is a fundamental aspect of the emerging new technologies, the connectiveness, networks and the Internet of Things, Augmented Reality, Addictive Manufacturing are also equally preponderant elements.

That triad concoction of the physical *versus* digital *versus* computation, all integrated in a mutually influenceable system of measurement, volatile and smart embedded devices represents the Industry 4.0 in a nutshell *(Figure 9)*.

The inter-connectiveness trait expands also to the schema representation: it promotes a sense of circularity and recursiveness. Something that is characteristic from another representation: Product Lifecycle Management (PLM).
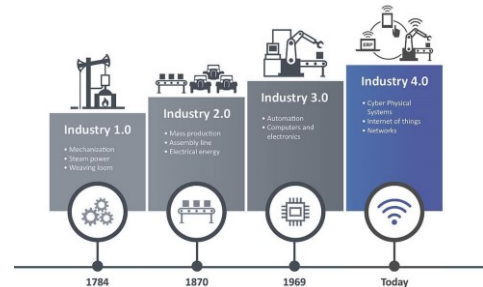
Figure 8 Industrial Revolutions (Source: ElectronicsB2B)

Figure 9 Industry 4.0 Technologies (Source: Medium)

The State of the Art (SoA) for Product Design Engineering (PDE) starts by identifying and showcasing use cases from the most recognized and prominent trends that exist today.

Firstly, two main concepts are introduced: the Product Lifecycle Management methodology and the Industry 4.0: both respectively represent the past-present and the future for the Product Design Engineering. The first also serves as a visual reference for the comparison of the use cases. The second gives the basis for the filter criteria, defined by buzzwords, that are currently more prominent.

Secondly, key-terms that are more relevant for the purposes and considerations of this document shall be selected and will be used as the main criteria for categorize the use cases. For each, there will be several sub-criteria. There the use cases concepts and paradigms will be explored.

The next chapter makes a qualitative analysis *(Denzin and Lincoln, 2000)* of the collected data: trying to standardize and set a common ground to make a general comparison between the examples. The method with how that was achieved was by using the PLM based charts as reference: locating the cases in product lifecycle wheel.

Finally, the conclusion drawn a compendium of the most relevant trends and its positive impact in PDE. Also, and that being the most important action, it will identify issues and constraints on use cases for the tools that can be explored later on in the empirical part.

Briefly and as a disclaimer: this SoA serves as an holistic identifier of the current more relevant and paradigmatic PDE tools. The focus being on the concepts, systems and paradigms, rather than an exhaustive and technical analysis. For that reason, every criteria and sub-criteria has an introductory text, followed by use case typology categorization.

2.2 Product Lifecycle Management

Product Lifecycle Management (PLM) is a management process that encompasses the entirety of an industrial artifact's lifecycle: from its conception to end-of-life. It is a management system for one or more products within a company. More than that: it considers, in an integrated way, all its direct and indirect constituents. Parts, instances and product portfolio. The Product Lifecycle Management (PLM) by itself does not have a clear goal: that is what each user or company imbue into it. Its implementation can bring many benefits from strategic up to operational ones *(Stark, 2015)*.

Although its origins are a bit dated, the Product Lifecycle Management process and set of tools remains not only relevant but crucial for today's industry.

Taking the scheme of things into account — for example the Information Technology (IT) companies' perspective in particular —, the PLM can be considered as one of the four basic and indispensable used tools in today's industry. For instance, all companies perform and manage their communications with either their costumers (Customer Relationship Management, CRM), their suppliers and fulfillment (Supply Chain Management, SCM), their resources (Enterprise Resources Planning, ERP), or their Product Planning and Development — all of them are derived from the PLM methodology framework *(Kongthon, 2001)*. Regardless of the previous more generic consideration of the PLM system integration, the latter is intrinsically more connected to a physical artifact: and the implicit necessity of quantity (industrial) production. In that sense, PLM a more relevant and adequate system to serve as comparison reference for the use cases — with that being used in academics already *(Lutters et al., 2014)*.

The description made above justifies the usage of the PLM as the pivotal reference methodology for this documents research and empirical experiments.

2.2.1 Product Lifecycle Management History

Although the Product Lifecycle Management (PLM) framework and methodology will be used as a main reference point throughout the document, it is not a "recent" concept. One can divide the PLM history into three main parts: its early predecessors, its origins and the most recent concepts and applications.

The first root appearance being widely noted as being from Otto Kleppner in 1931, which suggested the precursor of the modern product cycle understanding. He proposed that the products should go through the following 3 stages: pioneering, competitive and retentive. In 1957, Conrad Jones compiled a more recognizable organization and set of criteria that should be included in the product lifecycle: introduction, growth, maturity, saturation and decline *(Jones, 1957)*.

The second part began when the concept gained more traction, visibility and employment with its successful implementation by the American Motors Corporation (AMC), in order to gain competitive market advantage from General Motors. At this point it was evident that the Computer Aided Design (CAD) tools and the inter-disciplinary communications were two issues that PLM should address to optimize resources, costs and time product manufacturing. The system was so efficient that AMC was bought by Chrysler. From that, the PLM system gained much more visibility and would be developed to the scheme that is used today *(Figure 10)*.

As of today, the present-day state of the art tools: digital, decentralized and unified ones, start being integrated into the PLM methodology management. This fact — the transition of the PLM to an Industry 4.0 panorama: inter-connected —, makes the first one the most relevant and pertinent product management methodology to implement *(Staffeldt, 2015)*.

The PLM not only "makes sense", but it will build the bridge between all the remaining and conventional processes to a "4.0" era *(Rudeck, 2014)*.

Figure 10 PLM Scheme for Chrysler (Source: Web Archive).

2.2.2 Benefits of the Product Lifecycle Management

For all this it is safe to assume that despite of its quite dated origins, Product Lifecycle Management's efficiency and consistency is more than pertinent and evident — specially when considering its main targets in companies *(Table 1)*. Those being shorter time to market and reduced compliance risks, decrease of the costs, increase in productivity, quality, innovation and growth *(Stark, 2015)*.

2.2.3 Skills, Tools and Methodologies

The Product Design Engineer (PDEng) role requires a specific set of skills and roles. While the Product Lifecycle Management (PLM) scheme does not necessarily imply any specific technical skill, it always requires communication and integration actions. The distinct technical knowledge — the Designers and Engineers know Computer-Aided Design (CAD), the Manufacturing Engineers know Computer-Aided Manufacturing (CAM), the analysts and marketeers their own tools —, is allocated to each specialized group. The PLM presumes an encompassment of those and hence the communication and integration in a circular-like way.

Besides those, there are methodological tools and approaches that help to reinforce the Product Design Engineer role: Concurrent Engineering (CE), which is the parallelization and synchronization of tasks for time, and human resources optimization.
There are plentiful of other examples, such as Design for Manufacturing (DFMA), Quality Function Deployment (QFD), and Design for Six Sigma (DFSS).

There are variations and a multitude of other tools and methodologic approaches available nowadays. Their range and quantity is of such order that would be impossible to cover it here. The ones mentioned above are the most relevant to the industry at this given time. The number of tools and methodologies available today that derive from the core PLM chart are uncountable. This fact by itself proves the relevancy and pertinence of such system on today's industrial panorama of product developing and manufacturing.

Table 1 Product Lifecycle Targets (Source: Stark, J. - 2015)

Rate of introduction of new products	+100%
Revenues from extended product life	+25%
Part reuse factor	x 7
Costs due to recalls, failures, liabilities	-75%
Development time for new products	-50%
Cost of materials and energy	-25%
Recycling of products	+90%
Product traceability	100%
Lifecycle control	100%
Lifecycle visibility	100%
Revenues from new services on existing products	+40%
Number of significantly innovative new products	x 3

2.2.4 Product Lifecycle Management Representations

The PLM methodology historically converged into a more unanimous organization despite of the increasing variety and creation of new tools and new standards. Despite of that, its representation varies slightly in quantity, widely in quantity.

On the one hand it can be seen as a circular amalgamation of all types of influences — not only tools. People, processes, methodologies, technologies and data *(Figure 11).* On the other hand it can be isolated by its "production cycle", usually where it is only considered the market performance of the product, not the processes involved previously in the development *(Figure 12).* Finally, it can be seen as a mixture of the previous two: product lifecycle circularity represented only by its phases *(Figure 13)*.

The *Figure 11* represents a conjunction of all the potential intervenient in the PLM lifecycle. That representation corroborates the fact that PDE is indeed a multi-disciplinary confluence of diverse disciplines. Teams, Processes, Tools, Methods and Technology are the typology of criteria identified in this representation.

The second representation *(Figure 12)* explicit the expected curve with the 4 main different stages of product after its market introduction: Introduction, Growth, Maturity and Stabilization and Decline. They are both self-explanatory. It is a useful graph to inform the expected change of sells with the temporal progression from that market integration. Although it is a good representation, it does not consider the stages before — development and concept phases.

Both are correct in a sense — they accurately represent different aspects of the PLM methodology. From those, the characteristics that is useful to keep are: its circularity and recursiveness; its temporal and typology elements representation.

Figure 11 PLM (Source: Stark, J. - 2015)
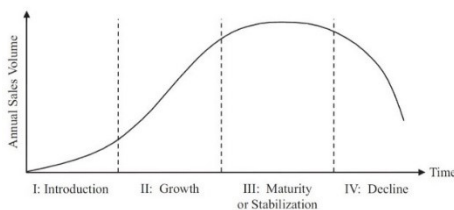
Figure 12 Product Lifecycle Curve (Source: Malakooti, B - 2013)

Lastly there is the simplified version of the PLM wheel: where it integrates only the key-actions along with the temporal relation — without excluding the repetitiveness and circularity of the system *(Figure 13)*. All of that in a more simplistic stance and specially regarding the development phases. This is the PLM representation that should be taken into account for the next chapters.

Corroborating this core statement, the PLM methodology is indeed more credible now than ever. Because the PLM methodology it is a reference point to the PDE practice, the first already has digital tools and frameworks implementations of it. The Product Lifecycle Management has current mainstream applications within digital software environments. Companies like Autodesk (with the Autodesk Fusion Lifecycle) *(Figure 14),* Dassault Systèmes (with ENOVIA) and Siemens (Siemens PLM Software) have their own version for it and because those are three of the biggest CAD software providers players on the market as of today that by itself proves the relevancy of the Product Lifecycle Management methodology in today's Product Design Engineering.

Finally, the New Product Development (NPD), a slightly more recent and updated approach to PLM, including a multi-stage communication between stages that were separated before *(Figure 15)*. This last one specially is key to understand one of the mains entropy and consuming action in the Product Lifecycle Management: — the inter-communication between teams. At some degree, this document will later on focus on the development of more elaborate solutions to solve that issue.

For that reason, with special attention to the latest updates and implementations — and without disregard for any possible negative aspect it can have that will not be addressed in this document —, one can derive that the system is as contemporary as it was in its origins and it is now more relevant and convenient than ever.

The PLM methodology process continues to be relevant to the PDE practice. As such, it will be used throughout the chapter of the State of the Art (SoA) for the reference between the use cases typology selection and comparison.
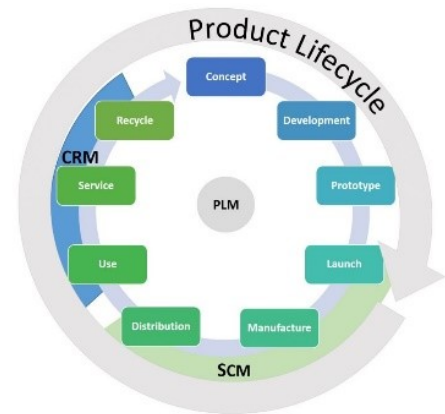
Figure 13 Product Lifecycle Management Simplified (Source: SmartSheet*)*

Figure 14 Autodesk Fusion Lifecycle (Source: Autodesk)

Figure 15 New Product Development (Source: SmartSheet)

2.2.5 Criteria Selection

For the State of the Art some specific selection and categorization of terminology was rearranged. There were several important reasons for that.

First, it was noted that there is still not full consensus about the integrant terminology and terms that constitute the Industry 4.0. As such, in a fuzzy-like logic approach, there are terms that are evidently more correlated than others.

For two, that correlation degree also suggests some kind of "derivation". Meaning that some terms are somehow "alienated" to the implicit core idea of interconnectedness (e.g.: Additive Manufacturing); as others have a much clearer and direct correlation implication such as "Sensors" and "Robotics". Three, precisely that idea of interconnectedness — suggested by the implementation of Cyber-Physical Systems —, is what defines the Industry 4.0 core ideas. The organization of elements around that precept is key to understand the decisions in the categorization and also the Industry 4.0 itself.

With all of this into consideration, it was possible to identify some major keywords, that can be fitted — although not belonging exclusively —, into the following generic categories: data-driven, accessibility and parametric.

2.3 Data-Driven

Data-driven is a terminology that encompasses any automated decision-making systems based in a pre-established set of criteria and algorithms; usually using a digital representation of physical object and external environment and making use of wireless technology interconnectedness of artifacts to amplify its network. In the Industry 4.0 (I4.0) data is king *(Soysal, 2017)*, and those who can explore this element have significant advantage in the any field.

One of the big buzzwords from the I4.0 is precisely the term "Big-Data". Although relevant, the specificness of this term is beyond the relevant scope of this document — where general Data-Driven decisions and criteria is taken into a much broader spotlight.

It is possible to identify undisclosed patterns and information in data when these two requirements are met: when it has considerable quantity and trustworthy quality — this last one being one of the pivotal focal points for Data Scientists to solve. Identifying that kind of concealed information is key to understand the rules that bound the Data-Driven products, design and manufacturing — furthermore, it is profoundly related with all the next two criteria: specifically with the "Cloud" (from the "Accessibility" sub-criteria) and "Cognitive Computing" (from the "Algorithmic" sub-criteria).

The two major buzzwords for this trend direction are: Internet of Things (IoT) and Digital Twin (DT). The latter derives from the second one, both temporally, semantically, and on the applications typology.

Contrasting with the rest sub-criteria, these two possess a high level of similarity: that is mainly because the DT is directly derived from the IoT — more like a sub-group. Making these two separate was due to the complexity and relevance of both: IoT is more generic and encompasses a wide range of terms and applications; DT is more specific, but the concept is radically changing the manufacturing processes — specially the maintenance aspect.

2.3.1 Internet of Things

As for many buzzwords that currently and ever existed in PDE and other areas, IoT is not a new term: — the term "Internet of things" was coined by Kevin Ashton of Procter & Gamble in 1999, although the term has been discussed in literature since the early 90's. The idea of Internet of Things is often misleading — as for every nomenclature that get some mediatic relevance —, where particular professions, people and institutions assign their very own adapted and convenient definition *(Kevin Asthon, 2010)*.

The Internet of Things (IoT) is a system of interrelated computing devices, mechanical and digital machines, objects, animals or people that are provided with unique identifiers (UIDs) and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction *(Morgan, 2014)*.

The IoT implies transmission, storage and interpretation of data at its core: real-time communication and adaptability of the system of artifacts. As said before, it heavily depends on technology and frameworks that shall be mentioned in the next chapters. The IoT is intrinsically related to the accessibility sub-criteria "cloud" *(Figure 17)*, that is going to be addressed later. Interconnected, decentralized and widely available systems are the bottom line for the IoT paradigm.

Figure 17 Internet of Things (Source: JustCreative)

The IoT is directly correlated to the Cyber-Physical Systems (CPS) mentioned in the introduction chapters: — the perspective that such systems will be able to automatically respond and react to stimulus is already a reality, with several consumer products and ecosystems already available in the market (like the Smart Home).

For that fact the Internet of Things terminology is probably the closest and intrinsically related to the Industry 4.0 general concept — not necessarily meaning that it is the most important one. Being that true, the inherent connectiveness is also one of its decisive characteristics *(Figure 18).*

Figure 18 Internet of Things Connectiveness (Source: Deloitte)

The analytic indicators are unanimous: from the 15 billion IoT devices in 2015 it is projected to almost double to 26 billion in 2019 *(Bera, 2019)*, with predictions getting exponentially higher by the day: the Internet of Things is going to take over. It is increasingly cheaper and easier to develop and deploy within this system *(Figure 19).* The question why is it a thing just now? There are several aspects and influencing factors that help explain that:

- Data generation: sensors provide analytical data;
- Data storage: storage devices and cloud services;
- Data transmission: internet connection;
- Data analysis: tools and computational power to data mine and analyze data.

The last being perhaps the most important and recently achieved element. The way algorithms can be designed *a priori* to any event is getting better: the Cognitive Computing Algorithms are making possible that such algorithms and programs adapt to new situations and can make the "rules" by themselves. That is the leading reason why this new aspect — not requiring human intervention —, is possible now.

To there are two key aspects that define and make IoT a reality: analytics and embedded systems.

For the first, the analytics correspond to the automatic cognitive-like systems and the concept of making the "rules" automatically. For the second, the embedded systems, the integration of the wireless technology and embedded sensors made possible for product-ecosystems — such as the Smart Home —, to be a reality in the consumer market. Combining both: the automatic and more reliable data processing and interpretation, with the data acquisition *in loco*, provide the basis for the concept to prevail.

a. Applications and Categorization of the IoT

The IoT is a complex and with a diversified typology deployment system. At an industrial level, Tao already made a complete visual mapping of its constituents, where he identifies 12 major areas and 54 applications for the IoT appliances in China.

Figure 19 Arduino (Source: Arduino)
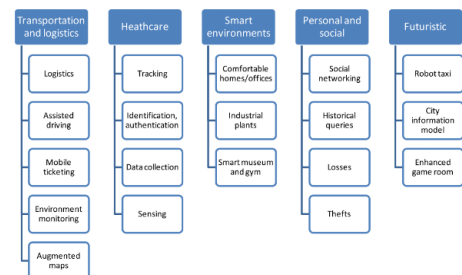
Figure 20 Internet of Things Categorization (Source: Atzori, 2017)

Atzori also makes a similar but more generic approach of the applications of the IoT, where he identifies 5 groups with 3 to 5 sub-criteria *(Figure 20) (Atzori, Iera and Morabito, 2010)*.

After the consideration of the categorization demonstrated in the literature, it was again evident the necessity of making an abstraction level up: a simple typology identification was favored on top of the "function" and specific applications. With that in mind, the following categorization big groups of IoT applications were set: consumer, commercial and industrial *(Tate, 2018)*.

b. Internet of Things Consumer Application

For the consumer category it was solely considered the "Smart Home" *(Figure 21)* framework environment. The filters for the selection were two: should rely on a central device as the consumer interface with the entire system — that possibly being computers, smartphones *(Figure 22)*, smartwatches or tablets two, it concerns also two functions: security and monitoring everyday actions.

Into those considerations, the sub-categories for the homme appliances are immense: its categorizations ranging from the type of home division, appliance, function and system. The list by itself is too extensive and unfolds into too many sub-branches to be represented here. Although, all those typologies were considered to the use cases (and are mapped as such). From those various appliances and products, the best examples were selected based in recognized review institutions. Those were the selected cases:

- Smart home kits: Apple, Amazon and Google;
- Smart plugs: TP-Link Kasa Smart Plug Mini;
- Smart light bulbs: Philips Hue White LED;
- Smart thermostat: Ecobee SmartThermostat;
- Smart security camera: Arlo Pro 2;
- Smart home security system: SimpliSafe;
- Smart door ringer: Nest Hello;

Despite of not being directly related with the Product Design Engineering domain (to what Product Lifecycle Management is concerned), its analysis gave some insights about the technology possibilities *(Cass, 2018)*.

Figure 21 Amazon Alexa (Source: Amazon)

Figure 22 Philips Hue (Source: Just Creative*)*

c. Internet of Things Commercial Application

In sum, the IoT applied to Commerce and businesses in general stands somewhere in the middle between the Consumer and Industrial. It demands the user interaction and concerns but with the bigger scales that are present in the industrial *(Tate, 2018)*.

Similar to the Consumer Application of IoT, the Commercial version scales and slightly changes the way the system operates, but always with the same underlying logic *(Figure 23)*. That scalability factor is key. The main use cases were:

- Transportation logistics and supply chain;
- Smart Building;
- Smart Retail.

Considering the Building and Business criteria:

- Hotels;
- Restaurants;
- Offices;
- Hospitals;
- Warehouses and logistics.

The complexity and variety could increase even more, but for synthesis concerns the categorizations and depth was keep in this level. The Commercial application of IoT starts to be more directly correlated to Product Design Engineering. Logically, its Industrial application is even more.

Figure 23 Commercial IoT (Source: Rigado)

d. Internet of Things Industrial Application

The Internet of Things Industrial Application or (as it is most commonly referred to) the Industrial Internet of Things (IIoT) follows the same precepts as its "mother-term" but with some different specificities. Its main argument is the integration of inter-connected systems and devices but with the main objective of optimization of consumption, time and energy management within a manufacturing line *(Figure 26)*.

The most positive prospect of this system integration is its perfect alignment with the Lean Manufacturing concepts, as it takes measurements and optimization into a whole other level of efficiency *(Sanders, Elangeswaran and Wulfsberg, 2016)*.

Figure 24 Energy consumption China (Source: Tao)
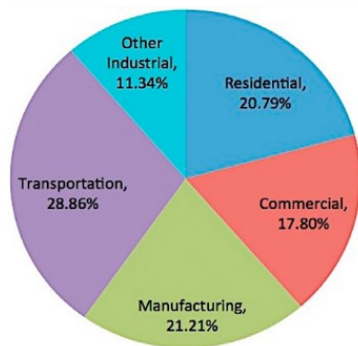
Figure 25 Energy consumption USA (Source: Tao)

Figure 26 Robotics Automotive Assembly (Source: Bainat)

That statement is corroborated by the statistical figures of the Chinese economy and the impact (energy consumption) that Industrial Manufacturing has *(Figure 24)*. Despite of not being as significant, the USA's economy also is heavily impacted by it *(Figure 25) (Tao et al., 2016)*.

The introduction of such system will equally have a heavy impact on the manufacturing process performance and efficiency. Ultimately, with the recent technology advancements and breakthroughs, this criteria will reach an unimaginable potential soon.

The use cases have two particular characteristics that must be pointed out: for one they corroborate the multidisciplinary integration of different disciplines, whereas the main benefit is the entropy communication reduction accrue from the implementation of such technology; second — this one not so positive —, the manufacturing (and commercial, eventually) is still very much constrained and circumscribed to the manufacturing or factory site.

This will be reinforced by the next sub-criteria "Digital Twin". The direct application of manufacturing process is somehow still dull and simples: — as the embedded systems are limited to the manufacturing machines and the direct measurement of their performance — their intercommunication being the incremental innovation. This argument will be indirectly pursued throughout.

Because of the mentioned above, the main categories for the use cases were as follows:

- Automotive industry *(Figure 26)*;
- General product industry manufacturing.

The mention of this sub-branch of the IoT will corroborate later on one of the issues with development endeavor focus for (but not only) the IoT. The usage of such technology seems to rely almost exclusively in the stages concerning the market lifecycle of the product — from its introduction in the market afterwards. That will become more evident in the following text.

2.3.2 Digital Twin

Under the umbrella of IoT lies a more specific application and concept. Digital Twin (DT) is heavily interconnected with its "parent" term from which it was derived *(Shaw and Fruhlinger, 2019)* — although it holds a much stronger appliance typology into the industrial and manufacturing panorama and consequently the PDE framework.

NASA was the first to introduce the concept in a more related and pragmatical way: *"digital twin means an integrated multi-physics, multiscale, probabilistic simulation of a complex product, which functions to mirror the life of its corresponding twin" (Glaessgen and Stargel, 2012)*. The usage of real-time dynamics and simulations with data from sensors and algorithms to better improve vehicle performance was pivotal, but the particular definition was the first relatable one with its modern definition *(Figure 27)*.

The Digital Twin it is a term already defined in the beginning of the 21st century, gaining more popularity over the year. In strict terms, a digital twin is a mirror image of a physical process that is articulated alongside the process in question, usually matching exactly the operation of the physical process which takes place in real time *(Batty, 2018; Romer, 2018)*.

The exposure of this terminology follows the previous Industrial context and presumes a pertinence of the factors that led to its emergence: the digital, real-time and algorithmic digital system representation.

There two relevant factors for applications emergence. The first is by type of industry: automotive. The automotive manufacturing industry have always assumed a "pioneer" role in leading technologies. The second being mainly geographical-cultural: China. The mainland Asian country is heavily investing in the system and technology, with some very interesting and paradigmatic use cases *(Tao et al., 2011)*.

To dive deeper into the term and give a conclusive answer and definition, an article created by Fei Tao was considered to explain all the intricacies present in the integration of the term into *(Tao et al., 2018)*.
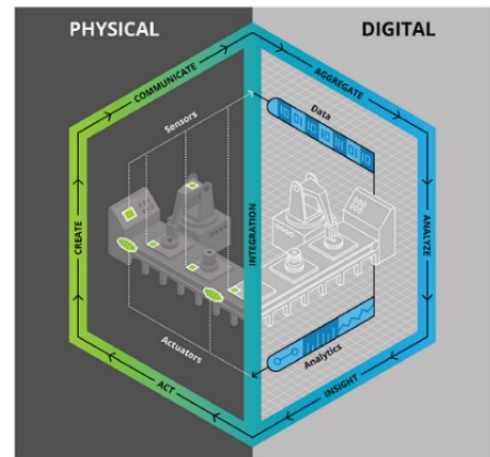
Figure 27 Digital Twin (Source: Deloitte)
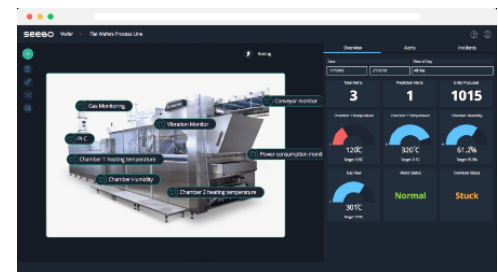
Figure 28 Digital Twin (Source: Seebo Platform)

2.3.3 Data-Driven Use Cases

The research and analysis of the use cases for Data-Driven (mentioned in the previous sections) served as the basis for two things: the identification of the groups; and how those will be referenced and compared in the Product Lifecycle Management wheel scheme.

Recapitulating, those were the main categories identified from the Internet of Things:

- Consumer;
- Commercial;
- Industrial.

Expectedly, the latter was the major focus of the research endeavors: not only for being more closely related to the scope of this document, but because the richness, variety and innovation of the use cases was objectively higher. From the Industrial Internet of Things, it was identified the most relevant industry companies — such as IBM (IBM Watson IoT), Siemens (Siemens IoT Services), Microsoft (Azure IoT) and GE Digital – Predix.

From there, the appliances and concrete use cases were considered[1]. The understanding through the analysis of those was exceptionally informative. The Digital Twin, although still in development, can already disclose some possible future use cases (some of them are actually already being executed *(Leeson, 2019) (Kitain, 2018)*:

- Quality management;
- Product re-design;
- System planning/virtual start-up;
- Logistics planning;
- Product development.

Finally, the represented groups in the Product Lifecycle Management for the State of the Art representation are:

- IoT Commercial;
- IoT Industrial;
- Digital Twin.

The consumer category was excluded for not being strictly related to the Product Design Engineering aim.

2.4 Accessibility

The Accessibility chapter encompass all the indirect related terms: the already mentioned interconnectedness — this being the closer categorization group in semantic terms —, interoperability and interchangeability, decentralization and new emerging and rich communication environments.

The presumptions of the 4th Industrial Revolution drives all things to some kind of "informed unification". The "things" need to exchange information and data seamlessly, between distinctive systems and frameworks. The way things are stored, interchanged and presented is going to be easier, coherent and richer, respectively.

From that big group, there are two main keywords that emerge as be fitted to this criterion: Cloud Computing (CC) and Augmented, Virtual Reality (AR/VR). These two terms do not share at a first glance any apparent relation. The "connector" is precisely the way they change inter-communication and perception. The first being by the decentralization of systems, and the second being by making the material more reachable and richer.

Accessibility is the means to which the data can be interchanged and accessed (Cloud) and represented (AR/VR). The IoT and DT base their conceptual framework on the assumption that those features in place. But not only that: the contained data itself can be read and interchanged between devices seamlessly — an universal and good-to-go framework that integrates data and devices in the same web of things.

Specially for the AR/VR, there is a particular promising development work being released. It is intertwined with the Cognitive Computing, particularly with the Computer Vision ones (in the next chapter). As for the CC, there is an overall integration of that property in several other sub-criteria — being almost taken more as an implied and assumed characteristic than anything else.

The universalization of the complete cycle: creation, sharing and interpretation (of data) is the core central concept from the Accessibility criterion group.

2.4.1 Augmented and Virtual Reality

Augmented and Virtual Reality (AR/VR) — which in this document will simply be rereferred as Augmented Reality (AR) —, is an interactive and digital experience that combines both the real-world environment with computer generated information. Although "augmented representations" are not exclusively visual, this document only covers that type of augmented applications and experiences.

Figure 29 Google Maps AR (Source: Google)

The way AR often works is by making some type of overlaying of those two elements, usually making that in a seamless and immersive way — so there's no human distinction from what's real or not. There are three features that should be met: that combination of the virtual and physical world, happening in real-time and that accurately represents the tridimensional registrations of those same physical and virtual worlds.

The distinctive feature from this technology is to seamlessly embed and admix the real and virtual world into a single experience: enhancing the first with the latter, generally. The term gained increased traction from 2016 onwards, due to the technological improvements that allowed devices to effectively attain the minimum aforementioned requirements.

The most common uses for the technology are:

- Games;
- Architecture;
- Real estate;
- Games;
- Tourism;
- Industry.

Figure 30 Microsoft HoloLens Industry AR

There are two mainstream mediums that can be used to employ an Augmented Reality tool or framework: a mobile device *(Figure 29)* (e.g.: smartphone or tablet) or a special helmet (e.g.: HoloLens or Oculus) *(Figure 30)*.
The first makes use of the accessibility and omnipresence of those objects and the second significantly more elaborate, allowing people to have a more immersive and profound experience.

2.4.2 Cloud Computing

The level of complexity latent and at what that type of given data operates readily increased in its preambles, only to allow to Product Development Lifecycle (PDE) digital tools to be deployed in such framework. Presently, in a more general sense like the Product Lifecycle Management or more specific tools like CAD/CAM have a plentiful number of commercial and enterprise applications.

In that context, the Cloud framework applied to PDE is often called "Cloud Manufacturing" and "Cloud-Based Design and Manufacturing" *(Figure 31)*. The premises are the same, with some changes in its transposition to the specific manufacturing panorama. Nonetheless, when that comes to play into the age of information — where connectiveness is implied —, it becomes a quite powerful and versatile system.

The more recent tendency is that Cloud or "online accessible" apps are incrementally gaining more popularity: starting to be a assumed feature in many state of the art digital tools for PDE. That traction gain is again justified for the simultaneous turning point in the computational power along with the internet power increase.

Finally the concept that integrates within the Product Design Engineering context is the Cloud Manufacturing (CM) or Cloud-Based Design and Manufacturing, is a framework of product development and manufacturing in which users can interact with it in decentralized application *(Simeone et al., 2019)*. That precept also serves as logic base for previously exposed concepts such as the Internet of Things — in which the interconnectivity of cyber-physical systems often makes use of this type of framework.

With that in mind, the concept of Smart Factory and consequently of the Industry 4.0 is totally dependent of the employment of this framework: where the concepts of automatic interoperability and interchangeability, distributed file system, web semantics and others are omnipresent (Schaefer, 2015).
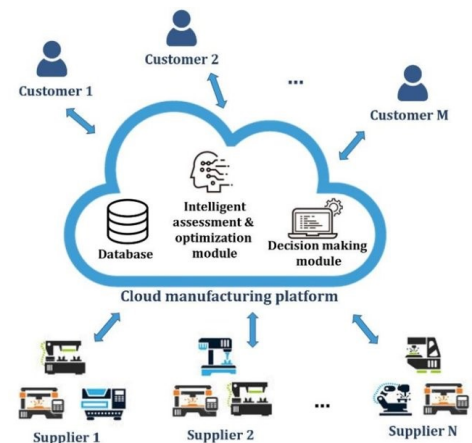
Figure 31 Cloud Computing (Source: MachTribune)

2.4.3 Accessibility Use Cases

The use cases analysis mentioned before, with was useful to denote the difference between mediums: Virtual and Augmented Reality Headsets and mobile devices. Establishing the distinctness and their set of pros and cons was essential to further understand and investigate the subject. The headsets give a more quality experience overall, but lacks the portability and convenience of the mobile devices. For the latter characteristic — for being precisely more accessible —, it was given priority to the mobile devices.

From that knowledge, the hardware, tools and only some constraints to its recentness. The most mediatic one being the Pokémon GO *(Figure 33)* released in 2016 — the peak of awareness and appliance of the then state of the art technology.

The most relevant use cases analyzed were:

- Gravity Sketch;
- The Wild.

The first one being an immersive framework for 3D sketching *(Figure 34)* and the second a collaborative environment for design and architecture teams.

Drawing from the last examples, the Augmented Reality main development areas when related to Product Design Engineering are *(Ergürel, 2016)*:

- Design & Development;
- Prototyping;
- Training.

This synthesis is specially relevant and explicit for the Product Lifecycle Management comparison scheme that is represented at the end of the State of the Art.

Finally, the benefits of implementing this technology in the Product Development Lifecycle are evident and diverse. All revolve around the core concept of "communication" — making things explicit, their will be error reduction *(Holtorf, 2019)*.

Figure 33 Pokémo GO (Source: IGN)
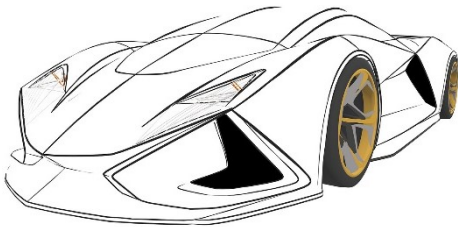
Figure 34 Gravity Sketch (Source: Gravity Sketch)

34

2.5 Algorithmic

Algorithmic is the third and last criterion group for the use cases analysis. Algorithms are, generically speaking, just a sequence of instructions represented by mathematical expressions. It is the basis on which computers operate — both in their essence, as their higher-level applications and tools *(Skiena, 2008)*.

So it is only logical that with the rise in the complexity, performance of the computer systems, their respective capabilities also increased correspondingly. As seen previously in the introduction chapters, the Product Design Engineering (PDE) tools are essentially digital as of today — although not exclusively.

The way algorithms helped reshape the way the "Engineering" and "Design" parts in PDE relate to the "Product" part is unprecedented and also too complex to be explained in detail in this document. The main and more consistent line of improvement changes being the automatization of tasks that were first done manually and now are done digitally *(Schaefer, 2015)*.

For this peculiar part, the chosen sub-criteria was purposively set into the specific displayed and announced order. The reason for that being that in a narrative sense, there is a logical sequence to that: incrementally adding in complexity and novelty of their corresponding and constituent algorithms. There is a sense of "succession" for each one of them. The sub-criteria chosen was (by order) the Parametric/Generative and Cognitive Computing Tools (CCT).

2.5.1 Parametric/Generative Design

In this section it is considered two sub-criteria in one. The reason being that they're both reciprocally and intimately correlated. Generative tools and frameworks derive — usually but not exclusively —, from the Parametric ones (hence the intentional given order in the title).

The first sub-criterion Parametric is the most well-recognized and used in today's doing in Product Design Engineering (PDE). Today, the number of tools and frameworks relying on this approach makes PDE completely reliant on this modeling process.

"Parametric modeling is a modeling process with the ability to change the shape of model geometry as soon as the dimension, value is modified. Parametric modeling is implemented through the design computer programming code such as a script to define the dimension and the shape of the model. The model can be visualized in 3D draughting programs to resemble the attributes of the real behavior of the original project. It is quite common that a parametric model uses feature-based, modeling tools to manipulate the attributes of the model" (Fu, 2018).

Parametric Modeling *(Figure 35)* has gained an omnipresent and indispensable status in the Product Design Engineering workflow. It is unthinkable of even conceiving of design, prototype and/or execute one product without heavily relying on that digital tool and framework — like the on that Figure 35 exemplifies. Historically, the implementation and development of the parametric tools is long, diverse and extensive. The one in referred in this document is the "history-based" one (pioneered by Pro/ENGINEER), and relies the 3D modeling on the adding-up of features to build an object *(Alba, 2018)* — and that funneling already implies both its history and conceptual framework.

On the other hand and inspired from that first sub-criterion, the Generative Design is an iterative design process that implies an iteration process with the main objective of generating automatically a certain number of outputs derived from a set of constraints (or rules). The process at its core is valid as long as that premise exists and it can be applied to all sort of mediums: from images to sounds.

The reason of Generative Design being so effective, is because it emulates the evolutionary natural approach in some sense: eliminating the ones that are not "fit" and maintaining the ones that meet the criteria.

Figure 35 OnShape Modeling (Source: OnShape)

To Engineering Product Design this strategy is particularly interesting and useful for it can generate solutions automatically. It takes a direct inspiration from that "modeling through features" paradigm in Parametric, making use of those features to serve as "constraints" that will construct the Generative solutions. Those criteria Generative features and criteria can be used in a multitude of objectives and aims: in Product Design Engineering from the morphology exploration to the topology optimization — although not exclusively.

Adding to those tools' capabilities, nowadays — specially from smaller companies' products —, there are a new set of arguments for those: instead of the old "performance", there is the decentralization *(Figure 36)*. Now most tools and frameworks have some sort of Cloud and/or web-based affiliation or articulation. The user is no longer constrained by either the physical access to the machine that has the tool installed or stored and not limited to the computational power of its machine. The "cloudification" of these tools and many others is indeed the future.

Figure 36 Onshape (Source: Onshape)

There are plenty examples of tools and frameworks that offer those capabilities: Autodesk Fusion 360 (from the big companies) and FreeCAD (a more open-source and free version). Despite of all that, none promotes that as the main characteristic and indeed none of them is an exclusively web based as the Onshape.

Perhaps the most interesting and relatable content with the empirical experimentation part is the InstantCAD example. The pivotal approach and focus of this tool is to allow a seamlessly and real-time adaptive manipulative mesh (often used in simulations) *(Schulz et al., 2017)*. The most interesting suggestion from the imagery is the manipulation of a rather discontinuous and deformable artifact, deconstructed and assimilated through features that can be manipulated at will *(Figure 37)*. That manipulation gets immediate response from the simulation on-go.

Figure 37 InstantCAD (Source: MIT*)*

2.5.2 Cognitive Computing

Following the introduction of the Parametric and Generative part, the cognitive computing is strongly based and inspired by those strain of solutions. Cognitive Computing Tools (CCT) solutions are characterized by one quite important aspect: their inputs are no human-deliberate. Although the most popular recognition of its application is exclusively associated with tech-like initiatives, cognitive-based solutions are applied in all sort of industries — specially in manufacturing processes in Product Design Engineering.

Figure 38 Computer Vision Scheme

The CCT encompass terms as Artificial Intelligence (AI), Machine Learning (ML), Deep Learning (DL), Natural Language Processing (NLP) and Computer Vision (CV). All relate in the way displayed in the *(Figure 38)*.

CCT reshape the problem solving algorithms paradigm approach. That be summed up by the subtle but overall radical difference of how one manages, input and manages data.

In traditional programming (or hard-code programming) — one that still prevails relevant today —, the code (the "rules") are designer in accordance with the data; that will then output an "answer". The obvious limitation in this approach is the variables and outlier situations that can occur: if something is not predicted in the code, the program will froze *(Figure 39)*.

Figure 39 Traditional Programming (Source: Tensorflow)

By contrast, in the Cognitive Computing Tools there is a high reliance on the relation between answers and data: which when held in high quantities and quality, allow to establish patterns. The output becomes a highly-optimized and data-based set of rules that will help solve similar problems *(Figure 40)*.

Figure 40 CCT Programming (Source: Tensorflow)

From the scheme in Figure 38 there is an outlier: Computer Vision (CV). CV is strongly implemented in manufacturing assembly lines today. It is closely connected to the Robotics and Embedded System areas. The capabilities of Image Processing allow for the manufacturing processes to be highly automatized.

Historically, the Cognitive Computing concept is intrinsically related with the Artificial Intelligence one. The latter was first coined in 1956, at a conference at Dartmouth College *(Buchanan, 2005)*.

From then on there were several milestones in its development, with some ups and downs on the way. The modern development of AI algorithms and tools was finally introduced with the research retaking by IBM, in 1997 with the IBM's Deep Blue: — which became the first computer to beat a chess champion (Garry Kasparov). The media implications were huge and there were several other milestones up to the present day.

Figure 41 IBM Blue vs. Kasparov (Source: Scientific American)

Finally, there are some elementary concepts that one should understand from the Cognitive-based world: Supervised and Unsupervised Learning.

Supervised learning can be either done for classification purposes — when the objective is to define the input to output labels —, or regression — where one can map an input to a continuous output. The most common algorithms in supervised learning include logistic regression, naive bayes, support vector machines, artificial neural networks, random forests and others. The main goal from both is to identify and take specific relationships, structures or paterns in the input data that allow for a correct action of the output data *(Figure 42)*.

Figure 42 Supervised Learning (Source: Medium)

The most common tasks within unsupervised learning are clustering, representation learning, and density estimation. In all of these cases, the main goal is to identify the inherent structure of data without using explicitly provided labels. Some common algorithms include: k-means clustering, principal component analysis, and autoencoders *(Figure 43) (Soni, 2018)*.
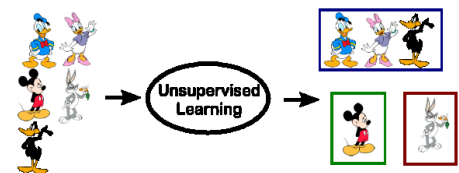
Figure 43 Unsupervised Learning (Source: Medium)

This thematic is highly diverse and complex: this sub-criterion mention is serving only as an introductory note for the more specific and technically informative chapter in the empirical experimentation part for PDE.

2.5.3 Algorithmic Use Cases

No doubt that the CAD modeling software available today is very well implemented in the industry and gets significant yearly release development updates that help tackle the learning and new features issues. Clearly enough, the "offline" CAD software solutions are still very much in *vogue* — Solidworks and CATIA from Dassault Systémes, SiemensNX, Rhino and Grasshopper, and Fusion 360 and Inventor from Autodesk *(Gaget, 2018)*. All of those have Generative add-ins and functions in all their software *(Figure 44)*. With that first consideration from the "big players" (Autodesk, Dassault, PTC, Siemens), the independent endeavors from startups and/or early stage companies give a much more interesting and insightful prospect of the emergent and truly State of the Art software *(Max von Übel, 2019).* Those were the most relevant:

Figure 44 Fusion Generative (Source: Autodesk)

- Onshape;
- FreeCAD;
- InstantCAD *(Figure 45)*.

Those last three corroborate the fact of the Parametric and Generative criterion being considered under the same section. They also establish a new evaluation standard from which some elements are as follows:

1. Being online and/or on the cloud;
2. Being open-source and/or free;
3. Allow multiple interchangeability.
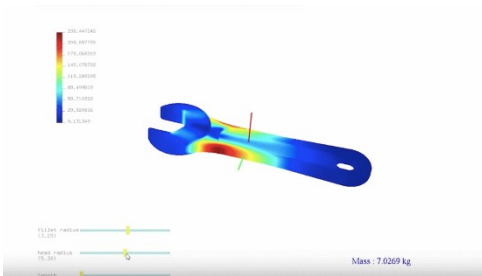
Figure 45 InstantCAD (Source: All3DP)

The revelation and usage of those criteria were pivotal to emancipate the direction to which CAD tools and frameworks is heading: towards the decentralization, like the premises in the Data-Driven and Accessibility criteria in the previous chapters. That last statement shall give rise to one of the issues and potential exploratory gap from the State of the Art — to be discussed in the conclusions.

Finally, the Product Lifecycle Management representation separates the Parametric and Generative from the Cognitive Computing criterion. Concluding: the potential future developments comes from the correlational sequence of the Parametric, Generative and Cognitive criteria is factually indissociable and inherently inter-dependence.

2.6 Product Lifecycle Management Referencing

This is the first set of conclusions from the generic qualitative analysis from the State of the Art regarding Product Design Engineering. It identifies the pinpoints and conclusions that will later extrapolate to the empirical experimentation part. For that reason the main consideration of the direction of the discourse in this conclusion part has the intent of uncover gaps and issues that can be explored in that later part. Each one of the three main categories have their own distinctive conclusions *(Figure 46)*. Each symbol and color represents a criterion and each number represents a sub-criterion: the graphical representation of their "influence" allows to uncover some of the gaps and potential exploration opportunities that will justify the experimental sections.
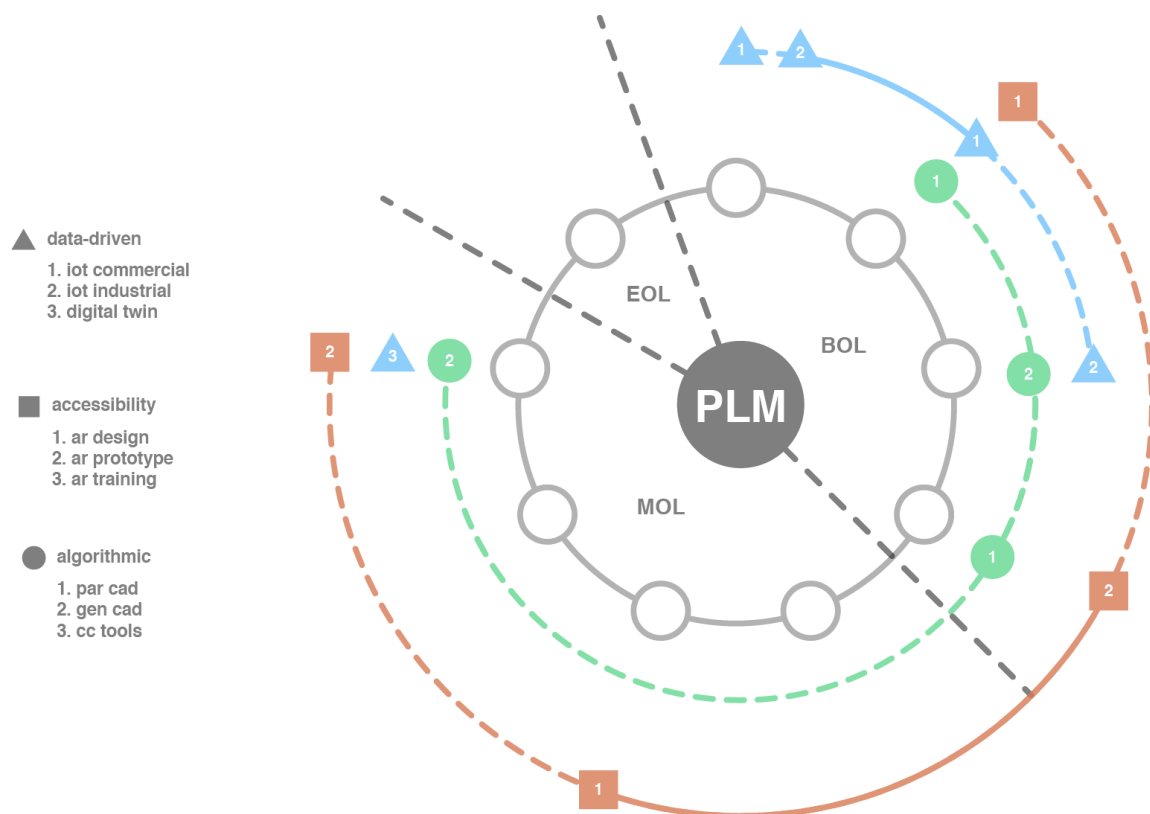
Figure 46 Comparison Scheme

2.6.1 Data-Driven: Internet of Things and Digital Twin

The Internet of Things as a system it is not a new concept but it is gaining some traction with new potential applications and arguments. The use cases analysis helped substantiate that fact: the Internet of Things its one of the biggest representatives of the Cyber-Physical Systems revolution that encapsulates the "4.0" paradigm shift.

Although this is a concept that relies thickly in the contextual computational and technological capabilities, that does not totally explains the recentness of its hype and applications.
Because the Internet of Things is generic concept representative of a system as a whole rather than concrete application or technology, its exploratory potential is much broader, unfocused and unlikely. In that frame of thought, its improvements appear unanimously: — whenever those technological advancements occur, it impacts the reliability of the Internet of Things.

Corroborating that fact is its blurred allocation in the Product Lifecycle Management scheme: it can be omnipresent as it not only represents the technological concept as a whole but also because there are commercial products as of today that employ this concept. The difference in this last part is for the Digital Twin: as of now, its applications are exclusively drawn to the manufacturing process — machinery, robotics, processes.

2.6.2 Accessibility: Augmented Reality and Cloud Computing

The Augmented Reality it is probably the most trendy concept exposed in this document: — it gained most of its attraction around 2016 —, which is coincident with the launch of the mobile app of Pokémon GO. Admitting that residual part of that traction has been decreasing up until now (2019), it is also useful to try to understand what are the repercussions of that: now that the excitement went away, it is an opportunity for more sober and reasonable experiments and products to be released.

As for its strictly related Product Lifecycle Management presence, the Augmented Reality applications are concentrated in the early and mid-stages: the later cycles are not usually covered, either by constraints or for no justification for the employment of this technology in those stages. The only appliance being in the products themselves, but that does not fit the criteria of relation with the Product Lifecycle Management.

The omnipresent characteristic of the Cloud Computing, cross-sectioning every single sub-criterion of every group criterion makes it an indispensable integration contender of the next years emerging technologies — more latent than clamant.

c. Algorithm: Generative, Parametric and Cognitive

The Algorithmic criterion group is also highly context dependent: meaning that the technological improvements always backup any breakthrough or shift. After all and simply put, those occur in a computer-based environment and those tools are bounded — for good or for bad — to that medium. Because the sub-criteria are incrementally more complex and specifically derive from the main criterion, they are also included in those constraints. For all them that dependence is quite pronounced but not absolute: in fact breakthroughs can also happen in the amidst of a relatively static time in computation technology development.

The parametric criterion is probably the most predictable one. By heavily relying on the CAD software tools, those are well established for a long time now in what Product Design Engineering is concerned. In that sense, the true innovation may come from independent endeavors (e.g.: InstantCAD) that can defy the *status quo* and input something entirely new into the field. Until that, the development happens with tiny incremental steps — as the industry is heavily reliant on those. Again, for the good and for the bad.

For that reason, there is no particular inclination or indication towards a radical new way of doing things. As it has been proven throughout it years of deployment and development, the approach works and it can adapt to very specific needs, situations and projects. For that reason there's no major issue or gap to be found on this sub-criterion.

As for the Generative solutions they are neither harnessing nor contemplating the possibility of enrich the constituent algorithms with more recent and emerging ones (e.g.: Cognitive ones). It is the most conspicuous fragility gap in this sub-criterion. That fault is substantiated by the ignorance of the human input — the current methodologies do not stop stressing the human dimension and "user-centric" approach —, then it is not surprising that the hype have slightly faded away.

The fundamental fault of those algorithms is not being able to recognize the "human user" as the central figure of their concerns. If design is created by humans, its pivotal concerns shall not be anything else. And for that, the idiosyncratic can only be attained by acquiring human input data.

If the features that are defined are neither capable of making use of the most recent Cognitive algorithms, nor to advocate human considerations, then there is a tremendous potential wasting in the solutions' generation and iteration.

The cases observed that represent the State of the Art offer nothing new and are nothing more than a spin-off with no adaptability and only taking advantage of the computational power incremental escalation, when considering those issues. So the question for that is: *why was it not made yet?*

For the Cognitive Computing Tools are not applied in the Generative analyzed use cases. That is a problem that, although it does not "belong" in this section — as the direction is the Generative methods integrating and not the other way around —, it has to be mentioned.

Besides that, there is a second aspect worth mentioning — that can be seen just by looking at the Product Lifecycle Management mapping results: — there is little or no evidence of appliance of this type of algorithms in the early stages of Product Development and Manufacturing directly.

That issue gets even more relevance regarding the tacit foundation of Industry 4.0: data-driven decision making. That also contradicts the tendency of the "enclosing circularity" of things, where everything becomes inter-changeable. Being the early development stages the first emancipators for the cost and time efficiency of any project *(Figure 47)*, this gap might be the first step towards a successful implementation of the I4.0 core ideas in PLM. This chapter's observation was already noted in previous academic works[1] *(Lutters et al., 2014)*.

The matter becomes even more flagrant if one considers the following arguments:

1. Lean methodologies (standard in manufacturing and product management) heavily rely in the "waste" reducing of all types;
2. The decisions made in early stages of Product Development Lifecycle are notably uncertain, intuitive and unexpected (for it does not usually have useful information at this point);
3. Cognitive-based algorithms and tools are particularly good at identifying patterns in disorganized (but also quantitative) data.

Their underusage does not go unexplained though: the main reason being that the current work that remotely approaches this contextual application remains in the academic literature — with still some prior work needed to be successfully implemented in the industry. In conclusion: this last sub-criterion shall be one of the central arguments that compels the endeavors' direction in the experiments.
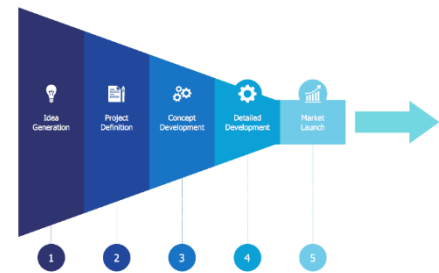
Figure 47 PLM Funneling

[1] Amongst the abundance of existing design tools, relatively few offer support to the conceptual design phases. Yet, companies do acknowledge that conceptual design determines at least 70% of the product costs and affects the total course of the design process. A likely reason for this uneven spread is that design information in the early stages incorporates many uncertainties. In many design contexts, this contrasts with the inevitable demand of software-based design tools to capture design information in a limited set of explicit variables. On one hand, this calls for tools that are less deterministic in nature and can better deal with indistinctnesses. Especially the need to project consequences of early design decisions on the further course of the project (e.g. by what-if analyses) leads to the expectation that many tools/ techniques will move towards the fuzzy front-end [...] or that dedicated tools/techniques will be developed. Such tools will have to rely on a new 'language' that can relate the indefinitenesses and relative vagueness of the fuzzy front-end to the specifics of the design environment. In this respect, requirements engineering will become an important asset for many tools/techniques, as it will facilitate the linkage between early stages of design to detailed design in a continuous process. Based on concepts like RFBS (Requirement-Function-Behaviour-Structure), semantics can aid in converting functions into the inception of (generic or abstract) structures. With this, the behaviour of a system can be predicted/derived and simulated, enabling an evaluation of the structure of the proposed system.

CHAPTER III . Architecture

3.1 Architecture and Urban Planning

The Architecture and Urban Planning (Arch&Urb) case studies derive from the work and experimentations done during the student's internship at the Luxembourg Institute of Science and Technology (LIST) from the month of June to November 2019.

Arch&Urb are two inter-connected and dependent disciplines, which some of its methodologies and tools are also relatable with Product Design Engineering (PDE). That fact it's extremely useful when making the following assumption — the tools and methodologies that are used in architecture (usually) can be transposed to the PDE realm. With the two practices being historically on pair, their usage in this documents context makes sense.

Also it is worth mentioning that despite of its similarities, they also carry a fundamental difference: the interaction relationship with the user. For Arch&Urb the user does not "carry" or "use" like it would use a product. Logically the emotional connection implied is different from PDE. Here the user "lives" in it. At its core, its function it's to protect it from the external environment. Despite of this an other fundamental differences, their reciprocal inspiration remains valid. They are mutually influenceable.

These previous paragraphs serve as an introductory note in the statement of similarity between both disciplines. That parallelism shall be given by giving some case study examples with the same categorization structure found in the Product Design Engineering State of the Art's (SoA) chapter. After that, two projects are going to be explored and briefly explained. The first one: "Quartier Alzette" (QA); the second one "SGI AR/VR". The ideas and statements from both will correlate to the inspiration used later on for the problem-solution definition in PDE, as well as they will more evidently corroborate the presumption of similarity between the two disciplines. That being the ultimate interrelation element connecting both.

Most of the environments and frameworks, as its solutions and issues that can found in PDE can also be found also in Arch&Urb. This circumstantial advantage shall become obvious with the discourse development.

3.1.1 Architectural and Urban Relation

For this first theoretical contextual section, the parallel concepts shall be introduced with the same structure and categorization as they were presented in the Product Design Engineering State of the Art chapter. Each group will be briefly introduced: the concept, the similarities and differences between Arch&Urban and PDE and, for last, the more popular tools and frameworks.

Figure 48 BIM Levels (Source: RIBA)

3.1.2 Architecture, Engineering and Construction;
Building Information Modeling

The first homologue will encompass the Industry 4.0 chapter and the Data-Driven criteria group: with the different terms being the AEC (Architecture, Engineering and Construction), BIM (Building Information Modeling) and CIM (Construction Information Modeling). However, only BIM will be used in this document.

BIM is a process constituted from various tools typologies and technologies with main aim of generating, manage and representing digitally the physical and functional attributes of places — expectedly Architectural/Urban ones.
The inherent correlated term is Smart Cities. In fact, that is an even broader term that can be used to encompass not only BIM, but some other technologies. The biggest revolution of the Smart Cities is to connect everything. But more than that: it considers the post-occupancy evaluation of the building — its data acquiring *(Daher, Kubicki and Guerriero, 2019)*. Although the BIM concept dates back from the 80's, similar to its homologue in PDE, it gained relevancy expressly due to contextual technological progress.

Figure 49 BIM Levels II (Source: Total BIM Make Over)

There are different level representations of BIM. The most famous one being by its original author, where it states it has 3 main levels *(Figure 48)*. Over time and attending to endemic constraints, similarly to the PLM, it can display alternative representations *(Figure 49)*. As a conclusion: the terms IoT and DT terms maintain its nomenclature, differing obviously in their contextual application — instead of a manufacturing factory, it considers a construction site.

Globally, the BIM concept is being more used in very specific countries and regions: in Asia it is in China (more specifically in Singapore); in Europe it is in the UK — the golden standard —, Central Europe and Nordic countries. There are other countries that are performing well, but for this brief it was only considered the ones that have mandatory BIM program in place — meaning that there is required by law to have some kind of BIM level in the building construction *(Shimonti, 2018)*.

In the United Kingdom there is a clear intention of walking towards a fully connected and intelligent smart city. Proof of that is given by the document "The Gemini Principles" *(Figure 50)*, from the Centre for Digital Built Britain, where it establishes key points and general guidelines that will help guide towards the connected future world *(Centre for Digital Built Britain, 2018)*. BIM is already mandatory for all government contracts. That says everything about how much the BIM is being taken seriously in the United Kingdom.

The common denominator for the Nordic countries is an institution called "BuildingSMART NORDIC". The included countries are Sweden, Finland, Norway and Denmark. Finland for example has the highest implementation rate in the world. At some level, all Nordic countries have the BIM as mandatory *(Biblus, 2019)*.

The last example being Virtual Singapore. It is an undergoing "dynamic three-dimensional (3D) city model and collaborative data platform, including the 3D maps of Singapore" *(NRF, 2018)*. Experimentation, test-bedding, decision making and R&D are some of the functions that will add benefits for the stakeholders, businesses and overall city *(Figure 51)*.

Overall the implementation and imposition of BIM is gaining traction, although there is big room for improvements and developments.

Figure 50 Gemini Principles (Source: RIBA)

Figure 51 Virtual Singapore (Source: NRF)

3.1.3 Accessibility

This chapter will be more focused on the tools and frameworks themselves rather than the generic concepts that encompass them. Retaking those concepts that prevailed from the homologue criterion in Product Design Engineering (PDE): Cloud Computing and Augmented Reality.

In the standards set by the Building Information Modeling (BIM) industry, it is implicit the use of digital tools. Also it is implicit a degree of interoperability and interchangeability: — a common denominator and system that can unify the way professionals work in the construction industry. For that is non other than the widely acclaimed IFC (Industry Foundation Classes) commonly used by every company that adopted the BIM methodology. A neutral data model developed by "BuildingSMART" — the UK government institution that promotes BIM —, that is intended to describe the AEC data.

Following that trend, the sub-criteria implementation is almost natural. For the Cloud characteristic, it is already "implied" for the BIM projects. That statement can be proven by looking at the Cloud feature in one of the most used software for BIM implementation: Autodesk Revit *(Figure 52)*. Along with the Forge implementation (an API also from Autodesk, used to access all programs from the group), it can have full Cloud implementation. But perhaps the more relevant example of the "Cloudification" of the BIM tools is offered by the number of AEC startups and independent endeavors that base their product solely on the web/cloud.

The AR/VR is in everything similar to the PDE when the lifecycle is concerned: — it has a prominent influence in the development and construction phases. Although it is not strange to see it being used now with the building already built. The cloud real-time realistic AR experience delivered by Matterport *(Figure 53)*, helps real-estate agents to reach customers with no need for them to be physically present.

Briefly: everything is identical except that there are use cases localized in the usage and post-occupancy phases.

Figure 52 Autodesk Revit (Source: Autodesk)
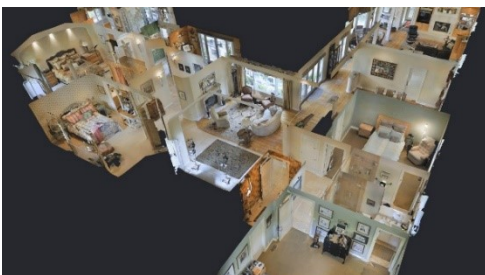
Figure 53 Matterport (Source: Matterport)

3.1.4 Algorithmic

Lastly, the algorithmic criterion that encompasses the parametric, generative and cognitive-based digital tools. The assumed process of digitalization stipulated by the Building Information Modeling (BIM) creates a strong affinity with general algorithmic tools. Again, for synthesis considerations, the mentioning work will take into consideration the three sub-criteria as they are —
as they are more or less reciprocally implied.

The first consideration and difference — more focused on the parametric realm —, is the separation of the paradigm in the CAD software. It can base its architecture in either the Textual Programming Language (TPL) *(Figure 54)* or the Visual Programming Language (VPL) *(Figure 55) (Daher, 2017)*. The VPL system is the most widely used in the architecture and urban applied digital software. There parametric tools existent in the AEC industry.

That research can be simplistically divided into desktop-based and web-based digital tools. The first focused on the Rhino's Grasshopper plugins — the ones used in the following projects *(Figure 56)*. The web-based was an arbitrary research endeavor to corroborate de decentralization theory that has been repeated throughout this whole document.

Grasshopper (GH) is a parametric visual programming language, giving the ability to write custom scripts to build parametric 3D models *(Figure 56)*. It achieves that by giving the user the ability to write its own custom scripts that can integrate a variety of other tools and frameworks. Its versatility makes it an excellent tool to prototype parametric simulations and artifacts. Dynamo, out of the scope of this main document, although very similar, is more BIM specialized — being a little less flexible. For all those reasons, GH was the framework used throughout all the experiments.

The parametric and editable properties of the Grasshopper and Rhinoceros allows the user to build simulations that consequently can be used to generate solutions based on the features and properties of the object. It is a recurrent and well-established exploring field, having plug-ins such as "Space Syntax", "Octopus" and "Magnetizing Floor Simulation".

>> print ('hello world!')

Figure 54 Hello World in Python
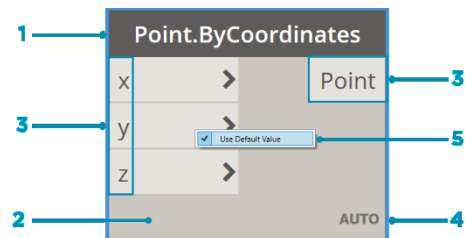
Figure 55 Dynamo (Source: Dynamo)
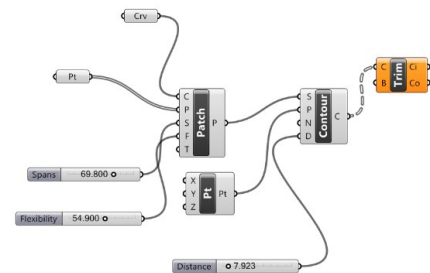
Figure 56 Grasshopper (Source: Food4Rhino)

In Arch&Urban the workflow and succession development of the sub-criteria contained in the Algorithmic group is much stronger and cohesive. The usage of CCT directly into the conception phase is something well entrenched: the cognitive-based decisions of plugins such as "LunchboxML", "Dodo" and "Owl" give a good impression of the level of implementation and personalization that those tools can already give to an architect.

Moving now to an enterprise level, there are several companies that are making it to the mainstream with the mixture of CCT and Arch&Urban creation processes. The most famous example being the atelier "Spacemaker" *(Figure 57)*, based in Oslo. In the academic level is possible to see some concerns about the measurement and interpretation of data with a cognitive approach, where aesthetic concerns are taken into account *(Seresinhe, 2018) (Figure 58)*, or simply the human response to the environment *(Ojha et al., 2019) (Figure 59)*.

Specially considering the last two examples, there is an emerging trend with the aggregation of the CCT and the Arch&Urban traditional processes. The way human impression is collected and interpreted can be referred as the Data Scientists do: human sentiment analysis. Only difference being that here the data is not generated from a digital world, but rather measured in the real-world *(Genc, 2016)*. Besides that imbuing of CCT into the design process, in the late stages of the Building Lifecycle Management (BLM) there are already examples of measuring and applying changes in the "post-occupancy" phase *(Daher, Kubicki and Guerriero, 2019)*. Quick note: the BLM corroborates the close parallelism that exists between Arch&Urb and PDE.

There is at a first sight a much more persistent work consistency in what the sub-criteria of the Algorithmic group is concerned. Both Parametric, Generative and CCT seem to have a well-founded basis and adaptation to the Arch&Urb challenges and functions. Now, that shall be tested next in the empirical experiment part.

Figure 57 Spacemaker (Source: Dynamo)
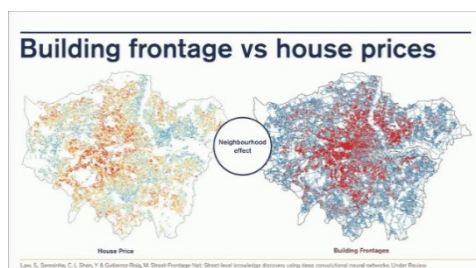
Figure 58 Cognitive Cities (Source: CogX)

Figure 59 Human Response Environment

3.2 Quartier Alzette: Simulation-Based Decisions Case Study

The first project is "Quartier Alzette". A contest held by AGORA for the urban planning for the "Schifflange" site, in Luxembourg — the name originated from that contest.

That initial contest had 4 winning proposals from ateliers from all around Europe. The evaluation criteria and constraints that made the evaluation panel were not evident. As that as one of the main motivations, it was decided to develop some kind of counter-proposal to those same winning projects.

One of the considerations from the original project briefing was the explicit preservation of historical landmarks — that is a visible trend from recent urban projects in Luxembourg.

3.2.1 Main Aim

The 4 winning projects will be the focus object for analysis and experimentation. The main aim is to first identify the contextual criteria that is relevant for this specific urban planning project, simulate and compare the solutions given by the participants with the optimal set of para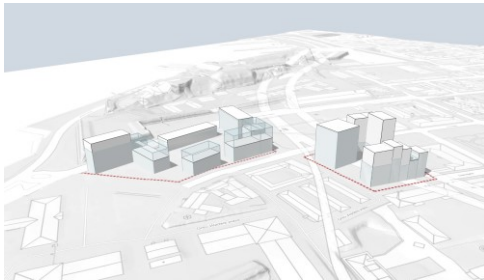metric set of criteria; and understand if it is possible to generatively improve the contestants and/or build a solution from the ground-up using that set of parametric criteria. Briefly, instigate two kind of solutions: contestant improvement and ground-up generative modeling through criteria setting.

3.2.2 Main Actions

The main actions and procedures of the project are divided into 4 main parts: modeling, criteria definition and simulation analysis, generative solution and workshop.
The first part, modeling, were the contextual site and contestants were modeled in CAD for later representation and analysis. The second, the criteria definition for the type and sub-type of simulations to be performed to be ultimately compared, verified and results be used in the generation of solutions on the third part. All of this to end in a workshop of participatory collaboration.
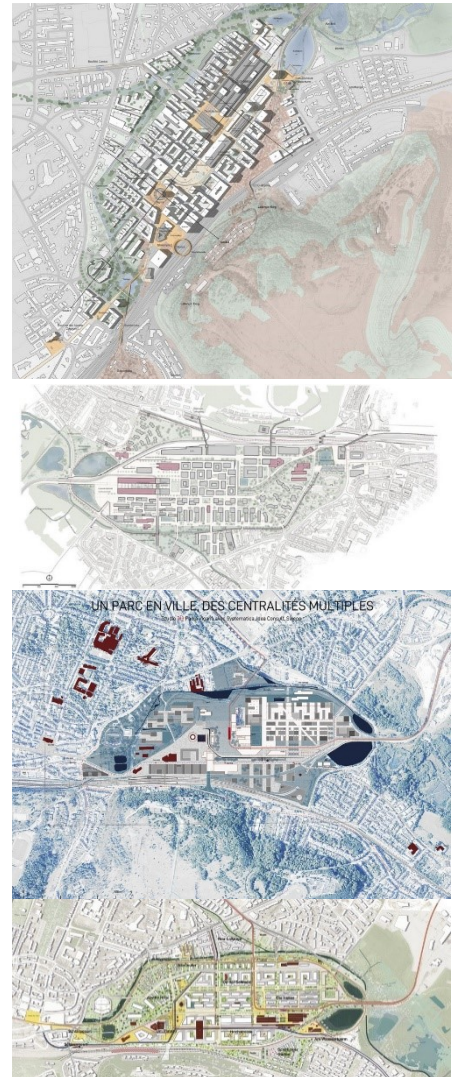
Figure 60 QA Contest Winners

3.2.3 Part I: Modeling

2019-06-20 to 07-10
Tools used: OSM, Adobe Illustrator and Rhinoceros 6.0;

The workflow of this part was quite straightforward. There were 3 main parts: first, the data export from the Open Street Map (OSM) website;

Figure 61 QA Contestants Modeling

3.2.3 Part II: Criteria Definition and Simulation Analysis

2019-07-10 to 09-05
Tools used: *specified bellow*.

The tool research was made not strictly for the Rhinoceros-Grasshopper software, although in the end it proved to be the most resilient tool to perform the job. That research can be comprised into two main categories: inside the Grasshopper parametric framework of Rhinoceros and outside of it.

In the end some constraints and interoperability consideration led to the exclusive viability determination and use of tools inside the Rhino-Grasshopper framework: where there was no issues of interchangeability of files format or risk of subscription fees associated with the use of such tools.

3.2.3 Part III: Simulation Criteria Categorization

For the simulation there were defined 3 main categories for analysis: well-being comfort, visual comfort, and mobility. Well-being standing for ambient and contextual factors that can influence indicators like light / shadow / radiation, noise and pollution. Visual comfort being represented by visual accessibility for sky, landmarks and overall interest points: green spaces, mountain and water zones. The mobility considered the accessibility with indicators such as distance to interest points such as: schools, healthcare, entertainment, bus and train stations.

For a deeper understanding of the subject and project, the report document can be consulted in the appendix with a regular structure and information disposal:

The documents are divided in 3 main parts, each one being a group that encompasses several sub-criteria (the ones mentioned above).

- Well-Being Comfort;
- Visual Comfort;
- Mobility.

The tools and frameworks used in the simulations and studies are as follows (by order):

- First: Ladybug (Grasshopper);
- Second: Ladybug (Grasshopper);
- Third: UNA Toolbox.

Each one of the main criteria has the following components and information:

- Tables and interpretation;
- Results for each sub-criterion;
- Interpretation and notes;
- Comparison and conclusion;
- Comparison (method) between criteria.

Represented in this document are only the conclusions and observations produced from that body of work — considered too extensive for the purposes and aim of this document.

3.2.3 Part IV: Generative Tool and Improved Model Generation

2019-09-05 to 09-12
Tools used: DecodingSpaces

For the Generative solution, the criteria and results from the simulations were used to obtain the reference points and features that would manipulated by the algorithm.
Two type of solutions were produced — as it was previously suggested: — one from the ground-up and another one based on the contestants solutions. The endeavor on this one was relatively shorter due to time issues, but the confirmation of the established hypothesis were unequivocal: the implementation of such improves drastically the design, efficiency and overall results from the solutions — in both its integrity or as complement.
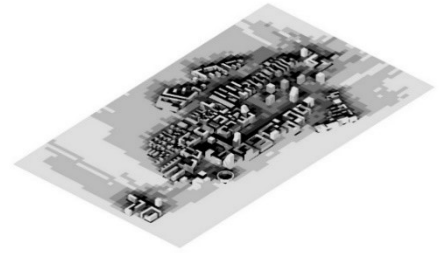
Figure 62 Contest 1 Shadow Simulation

Figure 63 Contestant 1 Radiation Simulation
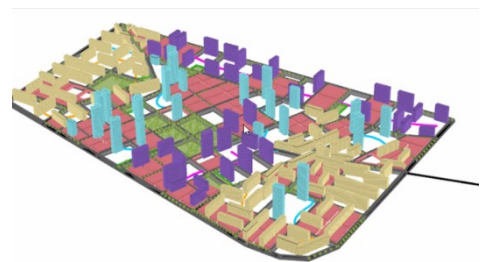
Figure 64 QA DecodingSpaces Generative

3.2.4 Results

The results from the simulations helped understand and corroborate some of the decisions made. Despite of that, it was not entirely clear in all criteria for all contestants — although that on the whole the results matched the decision made by the jury.

But precisely because there's not a clear usage of such tools from the contestants side, by inference one can induce that their designs could improve significantly through a (perhaps stronger) usage of such tools.

Nonetheless it is clear that there are benefits from the implementation of such tools — the designs, respectively, improved an overall score of 23%, 28%, 54% and 21%.

As a disclaimer, this was just an exploration methodology: the criteria setting, consideration and scoring might differ depending on a particular opinion or context — although it is held in high conviction that such changes should render non-relevant.

The learning curve from this type of approach to project and challenge solving was quite useful to clarify and enhance some methodologies that can precede any doing. The deconstruction (or synthesis) of the features of an artifact — being that Urban, Architectural or (ultimately) an Object —, remains forever relevant and useful and unveils some issues by predicting and patterning them.

Submitting to that exercise of an almost simplification and isolation of features of an artifact gives another perspective and approach that can save uncountable time and resources in the professional world. That is finally one of the conclusions that kickstarted the transposition of those very same theories to the Product Design Engineering world.

Nonetheless, in the end of the Architecture and Urban State of the Art and projects there is a conclusion that will corroborate and complete this last paragraphs.

3.3 VEGA SGI LIST: Augmented Reality Experiments

The second project was named "SGI AR/VR". The first acronym stands for the architectural company that had a partnership with LIST for this project and the second stands for "Augmented Reality" and "Virtual Reality", respectively.

3.3.1 Main Aim

This project was proposed in conjuncture with the SGI construction company and LIST research institute, in order to join endeavors for a partnership to integrate state of the art technology to enhance and optimized construction site processes.
The briefing was to develop a prototype demonstrating the possibilities of integrating AR with the BIM model onside during the construction process. The development and post-occupancy phases were also discussed but stayed out of the scope for first project.

3.3.2 Main Actions

The main actions consisted of researching the available digital tools for the implementation of the AR/VR — both including and not including Rhinoceros and Grasshopper. Second, the tests and implementation with exploratory experimentation and research. Third and finally with the demonstration of those tools in a conference to the business stakeholders.

Figure 65 SGI HoloLens usage I

Scenario 01 (3rd floor) – 3D Coordination
The modeling work focused on the development of the first 2 interactive scenes.
The first one set two main features: virtual building interaction and graphical interface embedded in the AR experience. The objective was to display artifact information when interacted with.

Scenario 02 – 7D Maintenance
Finally, the last remaining scenario resolution appeared: the 7D Maintenance (Objectif BIM, 2015). The main scope of the demonstration was to show the possibility of cross-check the virtual and physical model and extract issues from there: misalignments, defects, errors. The addressing of those problems without the need of a human specialist physically present can change the time and error reduction drastically.

Scenario 03 (3rd floor) – 4D Coordination
The second one being a creation of a 4D coordination tool: an interactive calendar that unified the referenced artifacts in the temporal panorama — hence the number detail in the scenario nomenclature. A Gantt-like calendar of dependencies and synchronized temporal works that are and should be done and the importance and delayed issues as well.

Scenario 04 – Exterior Facade
A simple exterior visualization scene designed exclusively to be seen in a mobile device and with no interaction. The unfinished site at the time of the final presentation event would be superposed with a finished virtual image of the building.

Along with this there were also some minor geometry and already made scenarios repairs.

Onsite test
Verification of features and scenarios as was done in the last onsite test, but including the newly made Scenario 02 with the 7D Maintenance.
Some other logistical decisions were made during this time prior to the presentation. For example the reposition of Scenario 02 from the basement for the 3rd floor.

Figure 66 SGI HoloLens Usage II

3.3.3 Final Proposal

The final proposal for the presentation was the implementation of an immersive and interactive experience for HoloLens, using the Fologram plugin for Grasshopper Rhinoceros. The 4 scenarios developed during the research and exploratory phase were presented.

3.3.4 Presentation and Resources

The people that attended the event were invited to try and experiment the equipment and resources — to later one give their feedback and talk about the underlying ideas and improvements that could be done. The resources were:

- 2x Laptop computers;
- 3x Microsoft HoloLens;
- Target Images (for referencing).

The final scenes for the presentation were:

- 3D Coordination;
- 4D Coordination;
- 7D Maintenance.

Again, for a full disclosure of the full extension of this project and the previous one, they can be consulted in the appendix section: the calendar, full explanation for the report, video presentation and photos can be found there.

As a remark note: there were several limitations from the usage of Fologram and Grasshopper.
The first is perfect for quick integration of Augmented Reality environments and together with Grasshopper, are one the best tool combination for the deployment of this type of projects. However, that easiness comes with a cost: the referencing system was still very limited, as not only depended in ideal conditions of light — not taking full advantage from the laser technology present in the HoloLens helmet —, but it could only use one target at a time — interrupting the fluidity of reference, that was constrained. The next proposal of future tools aims to address those problems.

Figure 67 SGI HoloLens Usage III

Figure 68 SGI HoloLens Usage IV

Figure 69 SGI HoloLens Usage V

3.3.5 Future Work

About the plugins that should be used.
The focus on the programming writing of a specific script, directly between HoloLens and some other program like Vuforia and Unity (where there is more editability).

Tools and frameworks to be considered:
- Unity AEC integration (Unity Reflect).
- Unity Digital Twin.

Actions to be considered and attained:
- The multiple target inclusion
- C# Integration

3.3.6 Results

There were several limitations on the usage of the Fologram plugin and the Grasshopper extension for the Rhinoceros software — a consequence of the process simplification, so needed to execute the project on time. Regardless, the pinpoint of this experiment resided in the people's reaction to the technology first hand — how they would perceive, accept it; but, most important of all, how they'd see beneficial the inclusion of such technology in their workflow — being the invitees almost exclusively constituted from professionals and stakeholders, that was a quite important test.

A questionnaire was taken during the event, where people could express their concerns, advices and observations about the system. From that constructive input it was possible to draw some conclusions. But, overall, the impact was unequivocally positive within the community: — generally, although aware that needs some development efforts, investment and time, the technology is surely the future of the AEC.
The benefits are evident, even within the scope of the meeting — people could interact and visualize with ease the BIM model of the building that was yet to be built. They could identify problems, issues, criteria and features that in any other way would take them much more time to grasp.

Truly, human perception plays a key part in the reducing of entropy between the different areas from AEC. One thing is for sure: this is the future.

3.4 Architecture and Urban Planning Conclusions

How does all of this relates to the scope of this document? To sum up: the first project explored the parametric tools' capabilities: first the ability to synthetize and reduce models to feature manipulation, that could be interacted, simulated and generated through various inputs. The second project showed the benefits of the implementation of Augmented Reality technology in an on-going construction site from Architecture, Engineering and Construction (AEC) with a Building Information Modeling (BIM) digital reference.

Drawing from those conclusions and considering that Arch&Urban are intrinsically connected to Product Design Engineering (PDE), the conclusions indirectly influenced and inspired the PDE project, in the next chapter. Those conclusions were:

3.4.1 Collaboration in Both Development and Post-Occupancy

The first big conclusion extracted from those experiments is the collaboration of people: the human factor as preponderant for the viability of results. Not only that, the human usage is crucial to simulate and understanding — in architecture that is called post-occupancy. So both in the development and usage phases, the human input is critical for a better algorithm design and parameter setting overall — because if we design for humans, why would not they be the best simulation and inspirational source?

3.4.2 Feature Synthesis in the Development Phases

In more abstract terms such as energy efficiency and space syntax, the right choosing of parameters and features is paramount for a good overall design process and solution. That was seen from the generative phases. Utilize the tools' computational available power in the early stages is of the utmost importance for cost and error production.

A side note: this particular criteria can exist without any human influence — their aim is to establish a blueprint that will serve as basis for the following development —, hence existing in the early stages. They can be deployed as a "verifier" as well. But presuming that they were used early one, should not give any unexpected results that would change dramatically the given design at the moment.

3.4.3 Real-time Interaction and Visualization Will Reduce Interdisciplinary Entropy

What the implementation of Augmented Reality tools will do is essentially automatize human interaction, not human work and influence. What happens is that they focus on the human interdisciplinary interaction, rather than focusing on human technical tasks. The real-time interaction and visualization that this tool allows will reduce dramatically the entropy that still stands today in a multi-disciplinary on-site work — specially one as complex as construction. That statement was corroborated by the questionnaire's feedback submitted by dozens of professionals and managers, but also by the explicit intentions of the SGI managing team — recognizing significant improvements of that sort would come from the implementation of such tools.

The empirical experiments made in Architecture and Urban Planning although quite distinct from the Product Design Engineering applicability of tools, they corroborate and reinforce the circular and interconnectedness schematic tendency that the new era of information and data-based tools is bringing. Although the evident proximity of PDE and Arch&Urban, that transposition shall not come without some caution. PDE is fundamentally different in some very specific aspects, namely the intimacy created with the user.

With that in mind and considering all the outcome arguments taken from the Arch&Urban projects, the next chapter shall be introduced. The inspiration and guidance was immensely influenced by this last one.

Chapter IV . Product

4.1 Product Introduction

The Product Design Engineering (PDE) project chapter comprises, as said before, two major influence contributors: the Architecture and Urban and the conclusions taken after the State of the Art (SoA) chapter. Recapitulating for the latter: the biggest identified flaw was the non-application of Cognitive Computing Tools (CCT) in early stages of the Product Lifecycle Management (PLM). With that and the previous chapter's conclusion into consideration, one can proceed to understand the underlying decisions and experimentation scope that will take place.

First, there is a theoretical introduction specifically for the Computer Vision tools applied to manufacturing and Product Design: a quick terminology explanation and contextualization, needed for the understanding for the non-technical reader to understand core concepts such as Convolutional Neural Networks (CNN) and Generative Adversarial Networks (GAN). The simplified theoretical introduction is imperative as it encloses the background and basis of the author's research. With that theoretical introduction made, it is analyzed a filtered set of case studies that are the basis for the enumeration of possibilities and technological capabilities of the present set of tools — the possible employable functions.

The framework, a collection of present and close-future possibilities, is a transposition of the ideas and concepts into a workflow that is likely to occur in parts or in its integrity. To perceive empirically the limitations of such framework, some testing applications were made to understand the involved constraints. The conclusions of such pragmatic exercise are unequivocal: they will allow to establish a hypothetical framework from the limitations and possibilities empirically observed.

The framework will be a hypothetical set of functions, applications and tools available (not only) to the Product, that will serve as a model of reference for the overall changes in the role of the PDE. From there, the conclusions will be based on the set of issues and risks derived from those identified major changes.

4.1.1 Product Design Engineering Concepts

From the last sub-criteria in the Product Design Engineering's State of the Art (SoA) it was invoked some further development into the Cognitive Computing Tools subject and intricacies that had some parts fairly omitted. The reason is because its specificness and still emerging condition of the techniques and tools makes it more suitable to be part of the empirical experiment itself — though it constitutes some addition to the SoA itself.

4.1.2 Computer Vision

Computer vision (CV) is a holistic and interdisciplinary discipline which aims to the general understanding of digital images or video *(Huang, 1997)* — more recently reconstructing in a "3D logic" as well. There are 3 specific sub-fields and paradigms that is important to know specifically here: Image Process and Analysis, Machine Vision (MV) and 3D Machine Learning (3DML).

Because Computer Vision is such a diverse and complex confluence of distinct disciplines, its history also becomes to extensive to be talked through. Although the most well-known first experiment is the one in the 60's, in an unexpected rather complex summer proposal project for a camera do "describe what it sees" *(Papert, 1966)*. A task impossible for the time, but not so much as of now.

Figure 70 Semantic Segmentation (Source: Analytics Vhydia)

4.1.3 Image Processing and Analysis

 Image Processing (and Analysis) in the context of Computer Science, simply relates to the acquisition and processing of imagery data and its manipulation through algorithmic processes. It is the basis on which the Computer Vision field is constructed *(Figure 70)*.

It digitally manipulates 2D image through the numeric representation of each pixel value: that is transposed to a matrix-like format. Most of the algorithmic approaches also separate the 3 channels (RGB), proved to be easier to manipulate and control *(Figure 71)*.
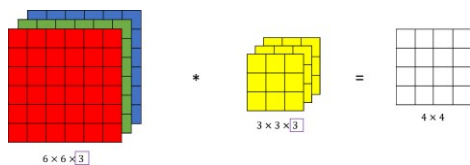

Figure 71 RGB Channels in the CNN (Source: DataHacker)

From those, the most conventional and used approaches are: Convolutional Neural Networks (CNN), Generative Adversarial Networks (GAN) and Auto-Encoders (AE). Although there are other relevant cases, those are the most meaningful to this document scope.

4.1.4 Convolutional Neural Networks

Convolutional Neural Networks (CNN) are a DL subclass applied specifically to imagery processing through multi-layered neural networks.

Throughout history there were several architectures that marked a turn point: such as AlexNET, LeNet and ResNet and others more recent *(Table 2)*. The core approach today remains essentially the same: that abstraction and subsampling of an image can be manipulated and accessed through tridimensional representations of the convolutions *(Figure 72)*.

This algorithmic approach can be resumed to dimension reduction and abstraction through a tridimensional approach and sub-sampling (image). The process can identify key features in the imagery that can be used to recognize and manipulate images. Interestingly enough, there is no consensus in the rational and logical explanation for the "why" these models actually work.

4.1.5   GAN's and Autoencoders

Generative Adversarial Networks (GAN) create two Neural Networks (NN) that "compete" against each other. That methodology produced astonishing results *(Figure 73)*, and one of its natural evolutions being the tridimensional artifact reconstruction from (multiple) images — a natural derivation from photogrammetry. In that field there are innumerous articles and literature trying to push the mathematic formulas to the limit — where the extreme would be that being made with just one single photo *(Han, Laga and Bennamoun, 2019)*.

Table 2 History of CNN Architectures (Source: Medium)

Year	CNN	Developed by	Place	Top-5 error rate	No. of parameters
1998	LeNet(8)	Yann LeCun et al			60 thousand
2012	AlexNet(7)	Alex Krizhevsky, Geoffrey Hinton, Ilya Sutskever	1st	15.3%	60 million
2013	ZFNet()	Matthew Zeiler and Rob Fergus	1st	14.8%	
2014	GoogLeNet(19)	Google	1st	6.67%	4 million
2014	VGG Net(16)	Simonyan, Zisserman	2nd	7.3%	138 million
2015	ResNet(152)	Kaiming He	1st	3.6%	
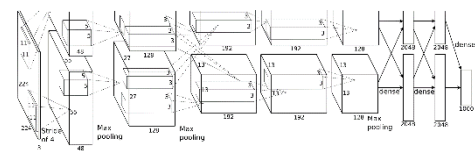
Figure 72 AlexNet (Source: Krizhevsky, Alex 2012)
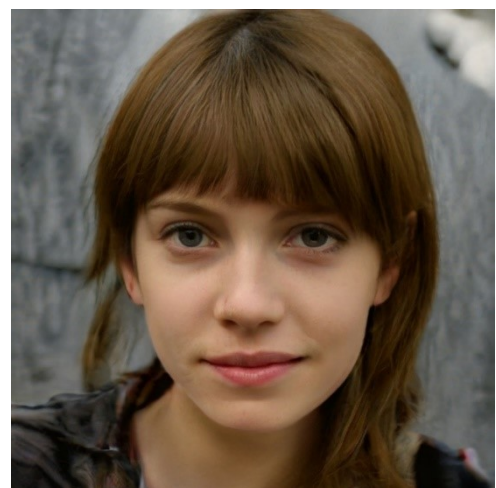
Figure 73 StyleGAN (Source: OwlsMcGee)

Autoencoders reproduce a representation of a data model, typically by dimensionality reduction (similar to the CNN). It is done by learning to represent that model in an "reversed" state — extracting the features from the process of dimensionality reduction and emulating them in a reversed way, but it different "tweaks". The results are so "believable" that, again, there is not a complete understanding of all the steps that led to the final resultant image.

Both of these solutions concentrate their applicability in the "reconstruction" and "generative" actions — a fact to take into account for the project part.

4.1.6 Machine Vision

Machine Vision (MV) is the specific application of the previously mentioned techniques and approaches to the industrial and manufacturing level: being this one specifically related to the PDE and PLM. The sub-fields of robotics, controls and embedded systems are often included in this framework. It relates in everything to Computer Vision (CV), just differing in the application context.

There are several examples of the possible and already undergoing applications of Cognitive Computing Tools (CCT) in product manufacturing processes *(Maguire, 2017)*. This blog post efficiently sums up all the key categories.

The Predictive Maintenance, using the Internet of Things (IoT) and sensors inside the machines for data acquisition and to predict failure in the working equipment. The CV directly implemented as imagery recognition can be applied to perform all sort of functions: defect reduction, package verification and information reading (such as barcodes). In sum, Visual Inspection (3D) applied to Manufacturing.

The implementation of CV tools and IoT systems presume a more unified and predictable manufacturing assembly line. The errors and issues can be not only predicted with much greater accuracy — because cameras are consistent and resilient —, but also acquire and process data in such way that the problems can be predicted — through cognitive-based Data Analysis.

Finally and as a conclusion note for this part: it was not so long ago that the automotive assembly lines were believed — and they were, in fact —, to be more efficient with human job preservation *(Nisen, 2014) (Lippert, 2018)*. There is a fundamental logical flaw implied in all the statements — that "there must be something special at the human level that cannot be replaced by the machines". Machines can evolve in their integration in such unpredictable ways — as they've been doing up until now —, that is more likely that they'll be successfully integrated than continue alienated in those particular tasks. Sooner or later, the machines will end the repetitive and automated work positions.

4.1.7 3D Machine Learning

"In recent years, tremendous amount of progress is being made in the field of 3D Machine Learning, which is an interdisciplinary field that fuses computer vision, computer graphics and machine learning" (Zhang, 2019).

3D Machine Learning (3DML) is the explicit relation of those three areas and relating to the understanding of tridimensional data. 3DML indeed the mixture of those concepts bring a whole different approach and understanding from the computational algorithmic models — that becomes particularly useful to the PDE discipline, since nowadays it relies heavily in the usage of CAD tools that (always) presume 3D data handling.

The complexity rises even more when methods of acquiring, process, store, manipulate and generate 3D data are concerned. Their foundation is relatable to the previous chapter's sub-criteria "Machine Vision".

For a comprehensive and quick understanding of the thematic and choice, some use cases in the sub-field will be introduced. Again, the exhaustive analysis and research is not explicated in the document, rather the most useful use cases were picked and showcased.

The two terms that it is useful to know is the LIDAR and Geometric Deep Learning (GDL). LIDAR is the 3D laser scanning technique that allow to gather 3D topology environmental information. It's usages are in self-driving cars and Augmented Reality helmets *(Figure 74)*. GDL is an emerging niche field that makes use of non-Euclidean (3D) data to the Neural Network systems — the understanding and connection of 3D properties to the Cognitive Computing algorithms *(Tong, 2019)*.

Figure 74 Microsoft HoloLens 2

4.1.8 3DML Tools and Frameworks

A clearer a deeper understanding of the 3D Machine Learning (3DML) discipline was required. This niche group is relatively complex and recent. As said before it is an amalgamation of different disciplines and contributions — some of them directly related with Product Design Engineering —, and because of its recentness, some of its work remains in the academic panorama: which is a corroborator of its emergence qualities but also puts the produced work in still experimental stance. Nonetheless, the disclosure of that research and discovering process and analysis — in a more tangible and simplistic terms, more than its technical analysis —, its crucial to have some insight into the author's decision and focus decisions.

The investigation was made with a progressively smaller focus point, as there was no "clear" milestone or objective. So that establishment needed to be done *ad hoc*.

The first tackle served to get a general overview of all the possible results from the introduction of Cognitive-based algorithms into 3D. With that was possible to outline the first set of categorization groups, that helped consolidate the conceptual mental model — crucial to further progress.

Some of the findings were immediate and particularly informative: briefly those tools exacerbate way beyond the Image Processing theoretical capabilities. It was clear that from the pixel-like information given by Image Processing, the algorithms were required to get some level of tridimensional understanding — although always within the imagery format. Single and multiple object, scene and texture detection, classification and segmentation was the overall finding.

Still within that first tackle and those first findings, some functions and constraints were also noted: in the "reconstruction" of objects and scenes there was always a logic of "training" with examples (datasets). That reconstruction was then made from relatively limited material — some of them even from a single photo.

After that first research investment and findings, some connections and presumptions with the posterior experimental part was forming. With that holistic basic understanding it was possible to go deeper and more focused.

There was two main actions from that second endeavor: another general assumption from the 3D data handling and a more focused categorization.

The first finding was that — specially with more recent academic work —, the data structure is starting to evolve from the Euclidean world to the tridimensional one, in representative terms.

The second action was related to the simplification of the categorization structure: consequence of the raised awareness and knowledge. That structure was now (by order): Detection/Segmentation, Reconstruction/Optimization and Generation/Interpolation. Both of their core concepts will be briefly explained as the last phase from the theoretical research was made.

With those category groups in place a new level of focus and understanding was needed: for the application and experimentation some in-depth analysis was needed — even if it was from a limited number of examples. The main aim was to perceive, filter and select the better and most emergent methodologies and investigation work that, even they were not to be directly applied to the empirical part, at least they will give a current and trustworthy insight into the present day technological possibilities.

Each function and selected literature was then chosen as the paradigmatic and/or better example within the field. A brief explanation of the function, criteria and the literature is given next.

The structure and case studies are as follows:

1. Detection/Segmentation
    i. Case 1A: YOLOV3 *(Redmon and Farhadi, 2018)*;
    ii. Case 1B: YOLACT *(Bolya et al., 2019)*.
2. Reconstruction/Optimization
    i. Case 2B: IM2CAD *(Pontes et al., 2019)*;
    ii. Case 2C: Image2Mesh *(Izadinia and Seitz, 2017)*.
3. Generation/Interpolation
    i. Case 3A: 3D-GAN *(Wu et al., 2016)*;
    ii. Case 3B: Implicit *(Chen and Zhang, 2018)*.

The Detection/Segmentation encompasses the detection and segmentation of objects via image processing and 3D understanding (Case 1B). The Detection/Segmentation is the best implemented function so far, with real-time algorithm execution. The Reconstruction/Optimization is topology understanding employed to fix incomplete (reconstruction) or faulty (optimization) geometry. Finally, the Generation/Interpolation is the synthesis of geometry into features so it can be either admixed (Interpolation) or created (Generation) from scratch or datasets.

Detection/Segmentation

The selected cases for the Detection and Segmentation functions category group was YOLO and YOLACT. Detection and Segmentation are the isolation of artifacts of interest in imagery through algorithms: the first only by classifying and detecting and the second by defining an "active" outline. The reason why being that this functions group it is already being implemented in several industrial applications: so the distinctive factor is not so much with its feasibility but, in this case, for its speed. Both imply, respectively, real-time classification and segmentation of objects. YOLO stands for You Only Look Once and it is as of 2019 in its third version — with some minor incremental improvements to its performance. It is a real-time object detection system. YOLOACT was one of the many work literature that explicitly derived from the latter: the same concept (real-time), but with segmentation — a form of object detection where the outline of the active and filtered object can be visually explicit *(Bolya et al., 2019)*.

Reconstruction/Optimization

Reconstruction and Optimization are also well established in industrial applications. The contextual meaning of the first relates to the 3D automatic modeling from imagery and the second — specifically in this context —, to the geometry topology optimization from reconstruction. The one presented in the State of the Art and respective case studies have a slightly different inherent meaning. Both papers — IM2CAD and Image2Mesh —, were chosen with its foreseen potential deployment of functions. The seamless interchangeability and automatic data generation between images and 3D data structures gives immense room for potential developments in Product Design Engineering.

Generation/Interpolation

The Generation and Interpolation are both a way of extracting features from understandable 3D objects and respectively do: for one iterate and generate within those detected feature or, for two, interpolate or admix within parallel features between two or more distinct objects. The case studies and theoretical explanation will be further explored in the next chapters.

4.2 Product Experiments

Attending the development of last chapters' investigation and work, the focus of the empirical experiments is now clearer. After identifying the gaps first and by exploring specifically the more technical State of the Art examples in the more recent chapters, it is now possible to exercise and conjecture the way of hypothetically deploy and execute the acquired knowledge into a digital product and solution.

This introduction serves to give some informative notes and the general omnipresent set of tools and framework that will be used throughout these empirical series. After that comes the project part: 3 distinct sections and approaches to different functions. The first two focus on some of the functions enounced before and the last one is an agglutination of all those into one exercise. In the end, some future perspectives and conclusions about the performed explorations.

Regarding specifically the isolated function projects, their structure will be as follows: one, function: recapitulation of the conceptual aim of the tool: the context, aim and objectives with this specific function experimentation. Two, framework and tools: the selected and the examples that were used as the basis for the deployment. Three, procedures: the set of experiments and actions that were taken to interact with the tool and/or conclusions by reading. Four: side notes with recommendations, file location and other useful information.

These series of explorations occurred in an environment of extreme uncertainty, so not all functions projects were explored equally: its time investment was heavily influenced by time-wise constraints, technical capabilities and objectives and aim. The final goal was to be aware — even in some very basic stance —, about the empirical deployment, and technical observations only verifiable with such approach.

The reconstruction/optimization criteria were excluded from the set of experimentation and considerations. There was not foreseen any advantage in that trial, moreover the timeline learning curve was way too demanding considering the remaining tasks and objectives.

4.2.1 Tools and Frameworks

There are some tools and frameworks that are omnipresent and remain the same throughout the whole project. One could call them "Elementary Tools". They are the basic environment upon the experiments are built and tested.

Assuming that those experiments, being digital, are to be in a computer-like environment. There are two relevant characteristics: the operating system (Windows 10) and the "specs" — despite of being important that those are relatively fair, there are alternatives for those that do not possess high-end hardware: Cloud solutions.

Figure 75 VS Code Software (Source: Microsoft)

After that, the operating software goes as follows by level of specificity and inter-dependence:

Code editor: VS Code *(Figure 75)*: the most widely acclaimed tool for programming as of today — objectively and statistically speaking; the framework includes multiple plugins integrations: code languages, online testers, live deployment, etc. It integrates the different environments into a single one.

Notebooks: Google Colab *(Figure 76)*: derived from the initial concept from the Jupyter Notebooks: an open-source web application that allows to run "live-code". Iterate through each line of code individually, adding notes and comments. The Google Colab Notebook is also a web application that allows that with the same properties than the Jupyter, allows the integration in the Google Drive (personal cloud file storing), making the work available anywhere at any time. Its deployment is seamless and instantaneous in any computer that has internet access. The accessibility was a personal requirement.

Figure 76 Google Colab

Programming Language: mostly Python 3.0 — it is the most relevant Data Science related programming language of the past years: libraries, packages, bundles and tools are overall optimized for this specific programming language. Although it is not very common, in these experiments that was the exclusively used one. The next chapters will disclosure those experiments.
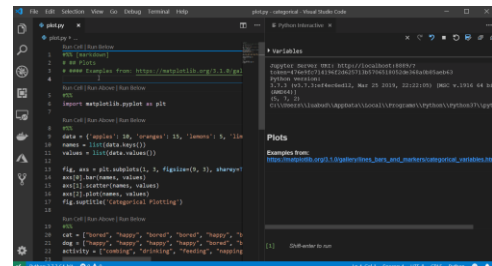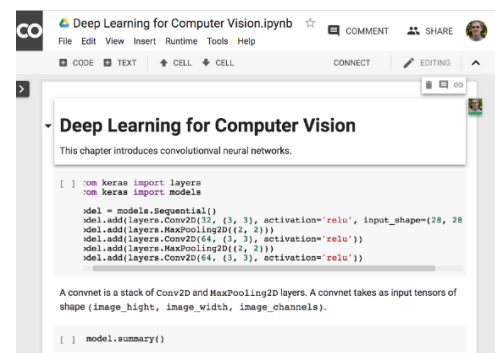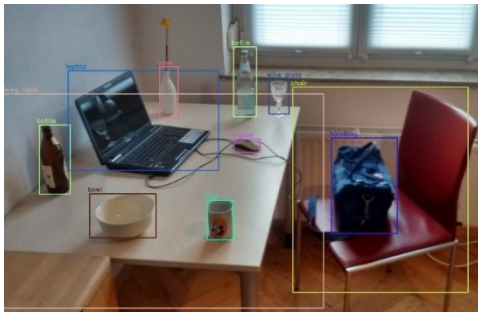
Figure 77 Example Classification
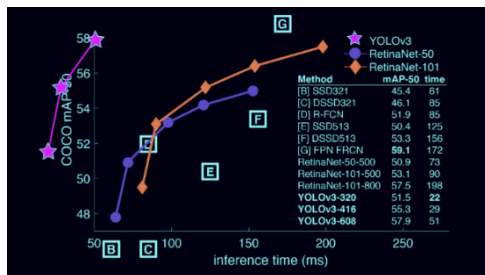

Figure 78 Segmentation (Source: YOLOACT)

Figure 79 Table comparing YOLO (Source: Redmond)

4.2.2 Object Detection, Classification and Segmentation

The Object Detection and Segmentation functions will be presented in the same section because they use identical libraries, frameworks and methodologies. Additionally they are semantically they are correlated.

a. Function

Object detection, classification and segmentation are three similar functions that act in a incrementally increasing complexity fashion.

Detection simply verifies the existence (or not) of the object in the active scene; the classification can distinguish two or more different (or similar) objects at the same time *(Figure 77)*;

Finally, the segmentation draws the "the active zone" in which the object is detected, with more or less definition *(Figure 78)*.

Whilst the object classification and detection by itself it is not something tremendously difficult *per se*, its deployment following particular constraints is. The one chosen for this project was the real-time object detection property (that property will be used in the same function as well).

b. Tools and Frameworks

"You only look once (YOLO) is a state-of-the-art, real-time object detection system" (Redmon and Farhadi, 2018). It is one of the most popular algorithms in which Machine and Deep Learning applied to Computer Vision.

It's distinctive feature being the real-time performance. YOLO significantly outperforms every other competitor at this very moment *(Figure 79)*.

The creator's name is Joseph Redmon, according to the site of his authorship, it is a CV worker that currently (to this document's publication date), is a student advised by Ali Farhadi.

- Libraries: YOLO and Darknet;
- Datasets: COCO;

Darknet is an open-source framework to train neural networks, it is open source and written in C and serves as the basis for YOLO algorithm. Dependencies include also the OpenCV function library and the COCO dataset. COCO is relatively large-scale object detection, segmentation and caption dataset. In Data Science, the usage of labelled and categorized datasets is extremely useful in the sense that the data is already compiled and ready-to-use or train for our own models. The YOLOACT academic literature serves as "segmentation derivation" from the original work from Redmond — only adding the segmentation property.

c. Procedures and Notes

The various type of neural nets and training sets are two separate things: the first is the "strategy" and approach to the intricate processing of the data and the second one is the temporary dataset upon which a particular case is going to be constructed.

There are 5 main phases in the experimentation, in which each one gets increasingly complex in its aims:

- Phase 1: usage of classification in an image;
- Phase 2: usage of segmentation in an image;
- Phase 3: usage in a pre-recorded video;
- Phase 4: usage in a real-time video;
- Phase 5: implementation in web and mobile.

For each one, there will be exposed the notes, observations and procedures in case one wants to replicate the results.

Before everything there was some testing and experimentation with very simplistic and basic concepts: the first one being training a data model by collecting images via Web Scraping — a method of automatically extract information from the web —, and trying to make some binary detection system through images. This experiment was made exclusively in Colab (in the next experiments was quickly realized that that would not suffice).
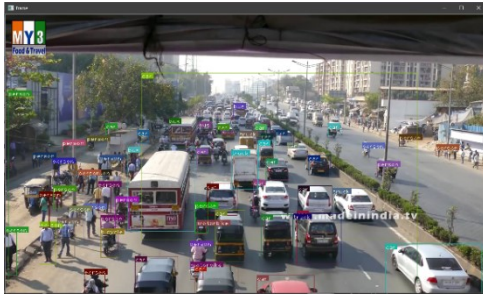
Figure 80 Object Detection Video

Figure 81 Detection Real-Time YOLO

Phase 1 and 2 were quite similar and relatable. As such, the biggest concern in this part was the technical verification of the framework — whether it works or not without any constraints or unexpected difficulties. Simplifying this first test set was key to just infer and develop the next phases without wasting too much resources. For that reason, a pre-existent dataset (COCO) was used to make this first set of tests. For those there was not any significant complication or observations.

If the latest phases were good for an initial verification, it was lacking complexity: as it was only a static image, its deployment was fairly easy and assumed.

The Phase 3 and 4 were more consequential than similar and aimed to increase that level of complexity by adding the real-time property. The Phase 4 was not initially planned, but it was almost a natural more ambitious exploration of the first successful cases *(Figure 80, Figure 81)*.

The first was fairly easier as the pre-recorded video has better quality, so it is easier for the algorithm to detect the right working features. The inverse disadvantage compared to the next one is that the higher weight from the images also led to some lagging and crashing issues. That was easily solved by reducing the file and complexity size. The file was only needed to be uploaded in the console and run through the NN.

As for the second, the biggest challenge was to deploy that in a actual real-time: on the webcam. The biggest foreseen issue was the frame rate — something that was denoted previously with the real-time pre-recorded video. Although the issues at that level were not as high, since the video quality was lower (and so the file size).
The result was a fairly decent 30 FPS real time detection of the surrounding objects that allowed. Nonetheless, the application of these frameworks allowed the deeper and informed understanding of this kind of issues — that would be definitely relevant if they were to be deployed in a real-world tool for Product Design Engineering projects.

The implementation of the segmentation function was once more a natural consequence of the previous functions work: this time the incremental complexity step up was focused on the "detection bounding box". The algorithm should detect and explicitly show — in real-time, again —, the "active area" that should outline with some accuracy level the object's location. The results were attained although there were still some frame rate issues. Nevertheless the experiment could be considered as successful.

The Phase 5 that corresponds to the mobile device application was indeed planned in the work procedures. Although due to time constrains, it was "displaced" for the ending chapter where the compendium of the functions will be made. Although it seems pertinent its "shadow" maintenance in the planning, because the works were heavily influenced by the final aim of integrating it in a mobile application.

e. Future Work

The results were never ideal, specially for the last part: as there was not as much development in the intersection of real-time and segmentation in image processing, the deployment was significantly more difficult. The implementation of a mobile and web version — perhaps even commercial — application. The possible applications to the Product Design Engineering field are later specified.

The next big challenges would be integrating some form of tridimensional understanding from, to and with the imagery: the PointNet paper is a manifestation of the first endeavors through that platform and data type richness increase *(Figure 82)*.

Naturally and again as a consequential development, the part and instance segmentation is also one of the close future works: it was not developed here due to time constraints, although some investigation was already made.

Also it was needed some more time to build proper datasets to see how autonomous is the construction of those — but as that was not a central concern of this work, it was considered secondary thus not prioritized in the experiments list.
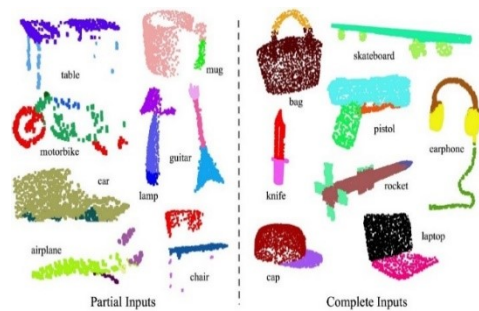

Figure 82 PointNet (Source: Github PointNet)

4.2.3 Shape Interpolation

This section is a direct response to the issues found in the State of the Art: the non-integration of CCT tools within the Generative tools. The increasing level of complexity and time constraints led to a more theoretical approach to this one: as the experiments were quite limited and not satisfactory.

The term "Shape Interpolation" stands as an informed solution generated from a binary — as it can be more than two examples, one can say "discrete" —, approach to generate a shape. A "blending" between two distinct artifacts with established common features.

Its exploration and consideration can open the doors for an active collaboration between the creative and creation endeavors characteristics in the early stages from Product Lifecycle Development and the more analytical and statistical informed datasets.

For that inherent complexity, the approach although still empirical, was less experimental and more for verification purposes. The depth of theoretical concepts and specificness of system also justifies this approach.

a. Function

Shape Interpolation has some different common assumed connotation: it is widely used in the 2D image processing with cognitive and Computer Vision algorithms. "Interpolation is making an educated guess with the information within a certain data set. It is a "best guess" using the information you have at hand" *(DeepAI, 2014)*.

In a more mental conceptual explanation: it "fills" the gaps of intermediary missing information. That abstractedly can occur at various types and levels in an image. Perhaps the more well known mainstream use cases are represented by the Adobe Photoshop tools. In the video format, there's also some undergoing investigation as well *(NVIDIA, 2019)*.

In the tridimensional realm the terminology application becomes rather complex and more focused: the intermediary aspect becomes literal — there is an almost binary conceptualization and parallelism between two artifacts that can be intertwined to form new solutions. The challenges are numerous: how one trains the program to establish equivalent features at different degrees between examples? Which degrees are the correct ones? How one produces a seamlessly and believable solution? *(Figure 83)*.

b.   Tools and Frameworks

Shape Interpolation is a concept that when transposed to the tridimensional world it can admix multi-feature objects into an entirely new one. The topology understanding evolves into a form feature synthesis and deconstruction: to isolate its volume, intricacies and design altogether so it can relate with equivalent relatable but isolated ones from some other element.

Interpolation in Latent Space

Figure 83 Latent Space Interpolation

Those are the characteristics of the benchmarks examples that are going to be explored in this section:

- 3D-GAN *(Wu et al., 2016)*;
- IM-GAN *(Chen and Zhang, 2018)*;

3D-GAN (Latent Space Interpolation)
The first example is relatively outdated for today's standards when comparing with other academic literature *(Figure 83)* — that corroborates the statement that it is virtually impossible to keep up with the rate at which this type of work is being published today. Nonetheless, this article establishes itself as a paradigmatic game changer, hence it relevancy as of today: — most of the work in this specific function is derived from the milestone that this one created.

The base concept a novel proposition made by this team of researchers was a probabilistic 3D object generator through space leveraging in contrast with the then traditional heuristic frameworks.
Using a voxel-based data format, the objective was to establish a low-dimension mapping of the object without CAD and image references, so one can explore the objects manifold.

Figure 84 Arithmetic Interpolation

Figure 85 Implicit Field Decoder

The first phrase that opens the work: "What makes a 3D generative model of object shapes appealing?" encompasses the one of the fundamental questions of this very same document.

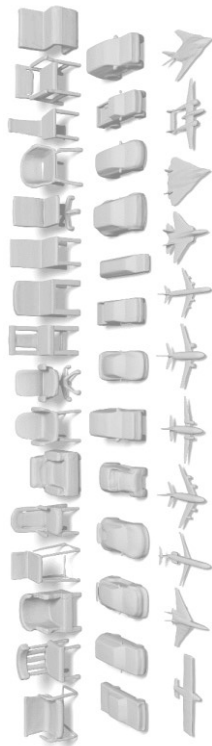Along the whole document it's revealed some interesting features such as reconstructing an object directly from one single image. The most interesting nomenclature appears when approaching the conclusion: the "arithmetic" and "interpolation" terminology — the latter inspired the terminology from that moment onwards *(Figure 84)*.

Those two extended the volumetric vector representations of the objects to a relatable one: the opening of those possibilities is the pivotal interesting point of relation with the aims of this document.

Creating something entirely different and at some point unexplainably distinct is a rather interesting possibility for the implementation in the early stages of Product Development Cycle. The potential of using the source of unexplained but data-founded inspiration through the synthesis of artifacts is enormous.

Despite of that, there are some fundamental limitations to this voxel-based methodology — noted when the source code from "Github" was simply deployed. The following works that had this one has basis solved most of the issues and added new optimization features.

IM-GAN (Implicit Field Decoder)
The previous work was pivotal and the source inspiration for almost all the work that succeed it. The Implicit Field Decoder (IM-GAN) *(Figure 85)* was one of the most impressive, notable and popular works within that subject: hence the choice of its exploration and emphasis in this document.

Indeed, graphically and visually speaking, the results' quality presented by this work are unseen in any other. The definition, criteria and standards that make the results with such coherency are astonishing. The geometry/mesh topology optimization was the main focus and argument of this paper.

There are some elements that make this document even more particular and additionally interesting: they introduce the paper by making some interpolation experiments with 2D letters. And that reference point is used throughout the all document. That detail of visual aesthetic sensibility and consideration is what ultimately sets this work apart from all others: using the algorithms and techniques to emancipate those characteristics.

In practical terms, by applying the code that was available on a open online repository, some improvements were noted when compared to the previous example.
Briefly, this all works with by an implicit field assigning a value to each point in 3D space, so that a shape can be extracted as an iso-surface. From there, the algorithm can optimize and relate with other examples — and making the geometry look nicer —, by confronting those diverse inputs. The results are bewildering.

Finally, in the document's conclusions, there is a future work compromise with including features such as part understanding and segmentation — another interesting and ambitious proposal that equally served as an inspirations for this document's work placement.

c.   Conclusions and Future Developments

Both approaches are paradigmatic in their own way — one by abstracting the form to its volumetric value in a voxel-logic way.The other one by implicitly assigning point-values and weights to the shape form and volume.

That understanding by "experimenting as is" revealed as of the utmost importance for the later postulations.

One thing is for certain: the understanding of tridimensional shapes and form is already attained. The question is when and how the performance necessary to be employed commercially will be attained — also its demand and necessity, although not as relevant.

4.2.4 Conceptual App Framework

The experimentation with different tools and frameworks allowed to perceive the fragilities but also the possibilities and room for improvement. It corroborated its viability for future tools' development. The natural consequence from those isolated experiments is its admixture and culmination into on single hypothetical exercise.

As the closure for the empirical experimentation phase, all of those experiments were transposed into a single conceptual exercise — a hypothetical representation of what could be if those were to be conjugated and coordinated into one single group.

The consequence was finally a conception of an Augmented Reality Mobile App for Early Product Development Engineering Phases. The primary focus was to conceptualize and explicit the basic features and their integration into the workflow, rather than solving its technicity — that it was already perceived from the previous chapters.

The core idea is to conserve the basic asserted features and basic concepts from the previous chapters: — Cloud-Based solutions, implementation of cognitive-based algorithms for problem solving. With that in mind, the isolated functions can be integrated into the workflow: Detection, Segmentation, Interpolation. Its specific and adapted functions will be explained next.

The main academic work that served as a conceptual basis for this part was a recent article not yet published but disclosed by the author: SDM-NET *(Figure 86) (Gao et al., 2019)*. It is an interesting work that follows the exact same pretext and inclinations of this work — it was published at a final phase of the writing of this document *(Figure 87)*. The interesting part without much coincidence, the author works through a framework, more from the technical Computation Science and algorithm design.
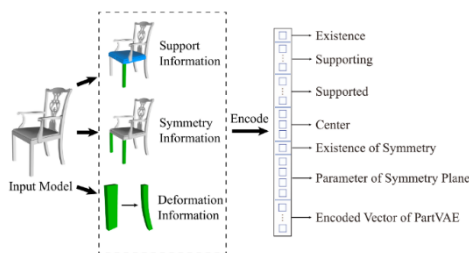

Figure 86 SDM-NET 1

Figure 87 SDM-NET 2

86

a. Tools, Frameworks and Results

Following the empirical knowledge from the experiments, it is to be expected some constraints in the development process. The biggest challenges in the deployment of the functions into a mobile-device app will be as follows:

- TensorFlow Lite: The TensorFlow is an open-source deep learning framework, with it "Lite" version having a reduced impact and resources. It is ideal for mobile and IoT devices implementation.
- Flutter: A development framework for mobile applications that uses Dart programming language. It is ideal for on-go deployment and app design, as it includes in its kernel both iOS and Android deployment. Simultaneously.
- Firebase: Firebase (from Google) is a mobile and web application development platform.
- Tiny YOLO: The mobile version of YOLO, considering its implementation in mobile devices as well.
- ARCore: As the most important feature in the deployment of the app. This Augmented Reality platform for both Android and iOS devices easily deploys some features that are to be integrated by default in applications of this type, such as: planar surface orientation, target indexation, libraries and other function implementation.
- Android Studio SDK *(Figure 88)*: The Android SDK (software development kit) is a set of development tools used to develop applications for Android platform. The Android SDK includes the required libraries to complement Flutter.

Figure 88 VS Code and Android SDK
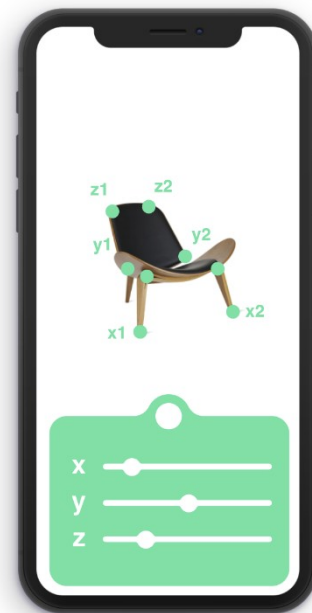
Figure 89 Concept App Feature Extraction

With this set of tools and frameworks it is possible to informedly conceptualize a mobile device application that would admix all the features and functions previously researched.

The first function Detection *(Figure 89)* is represented by the intermediate phase of feature detection and synthesis (visually). The weight points should be easily manipulated with the seen object.

Figure 91 Concept App Interpolation

The second function Segmentation identifies both outlines of the complete artifacts and its components. This detailed detection when cross referenced in between databases can provide the information belonging to the remaining Product Lifecycle Management professed throughout this document.

The third and final: the Interpolation *(Figure 91)* was seen as the function with the greatest future potential. The reason is, repeating, not only because of its mobile implementation and accessibility: — integrating this (and others) function into the Product Design Engineering early stages, the Cognitive Algorithms shall make sense of the "noise".

Helping and contributing the user creative and creation doing with less confusion and noise where it is not needed is the main aim of this mobile application *(Figure 90)*.

Figure 90 Concept App

b. Future Endeavors

Although the complexity and elaboration of the experiments was rather simplistic, its range was comprehensive and sufficiently informative about the state of things and the emerging future to come.

Being overwhelmed with the possibilities that can be developed from this tools and frameworks is unavoidable. That creation and creativity approach was always the leading reason and intention of all this document's aim: (just lik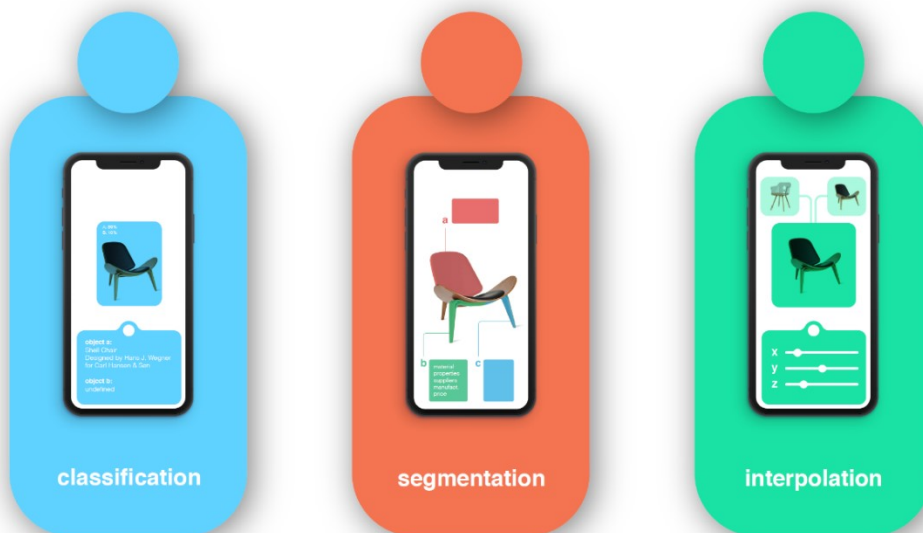e in the State of the Art) the objective was not to be fully and technically irreprehensible, rather to strive and experiment pragmatically with the new emerging techniques.

As so, some of the ideas that flourished during those experiments:

- Information about the BOM, fabrication processes;
- Could give semantic information and create an ontology about the inter-dependencies between parts;
- 2D drawings and 3D objects could be exchanged seamlessly using reconstruction algorithms

Despite of that, one of the consequences from the tridimensional understanding might be something even more ambitious: the possibility of Tridimensional Aesthetic Evaluation. The applications would be:

- MVP in aesthetic, style and semantic terms;
- System of patent verification and protection.

This would require the deployment of two quite hard tasks. For one, the full tridimensional topology understanding and, for second, the understanding of human perception of that topology — its pleasantness —, must be fully understood as well.

The conversion of the Design in PDE to a more clearer and scientific light can only prevent the appropriation and misleading and poor-quality that can be seen in the field. A Data-Driven conceptual framework will only rise the quality and make the Product Design Engineers' decisions more crucial than ever before.

c. Experiments Conclusions

Aside from all the constraints that were verified, the current digital tools and frameworks' capabilities are unprecedented: beginning with the possibilities introduced by Computer Vision that are extended by the 3D shape understanding brought by that and the "Shape Interpolation" like resources. In retrospective, it was possible to simulate and test very impressive results with such little resources.

With this, those tools nowadays are undoubtedly **faster** —, not only for today's increasingly computation power, but for the optimization in the algorithm's and software's performance. They are more **accessible** — in the sense that they can be accessed and edited anywhere without any compromise in the security. More **reliable** — the failure is minimized to a point where we can trust tools to fill the gaps of automatization without any risk of compromising a project delivery. For last: **more human-like** — this only stands for the effectiveness of the cognitive computing algorithms. The tasks where the entropy stand — communication and interpretation of data, specially —, this is where this kind of tools come in hand.

With all the acquired empirical experience is possible to informedly dissert about the future possibilities that might emerge from this kind of tools and frameworks.

Product Design Engineering will undergo some fundamental changes and repositions in the upcoming near future due to those tools. The increasing computational power along with the algorithm and hardware development will make those tools not only faster and more reliable, but more accessible through any device to anyone.

The eminence of those tools' surging is inevitable. Devices and network reading and action systems will become more autonomous, quick and reliable, the immersion of augmented representation will become more accessible and rich and, finally, the implementation of the cognitive based algorithms and tools will allow the implementation and the commercialization of these types of solutions with these kind of functions and use cases.

Chapter V . Conclusions

5.1 Product Design Engineering Challenges

5.1.1 Product Lifecycle Management Transition to the Industry 4.0

Drawing from the late conclusions in the introductory chapters from the State of the Art (SoA), the Product Lifecycle Management (PLM) shall be still represented in its donut form *(Figure 92)*. As for the empirical chapter: the way technology and tools can be applied today is unequivocally beneficial — and its implementation in the PLM is not only useful; it is inevitable. And the changes that those imply as well. As seen previously in the SoA, the I4.0 is introducing a new set of technologies, tools and frameworks. Despite of those being accurately represented by each node individually, it does not encompass the core idea that the I4.0. It is not fully represented. What truly (and also) characterizes the I4.0 paradigm in its essence it is the reciprocity and inter-dependence of its contained elements — meaning that the information and influence happens in every way, through every and each single node *(Burke et al., 2017)*.

For all those reasons the I4.0 advocates the basis for interchangeable information and comunication from the cyber-physical systems. Henceforth that representative element — the inter-connection between nodes — can be also transposed to the PLM scheme *(Figure 93)*. This type of representation in the PLM scheme makes all the difference at the conceptual level. All type of inter-actions between the different Product Lifecycle are connected and unified. Each node represents logically a stage in the PLM, and each one can contain several tools and frameworks — that can also not be constrained exclusively for that stage, extrapolating throughout two or more elements in the wheel. That inclusion corroborates all the observations made throughout this document: the reducing of entropy between the different phases and teams is the core benefit of the Industry 4.0. Although the scenario is well established as of this day, there is yet still a lot of work and development to be done — corroborated by the constant verification of the underdevelopment verified in the early stages of the product when it comes to the implementation of the tools that belong to this type of framework.
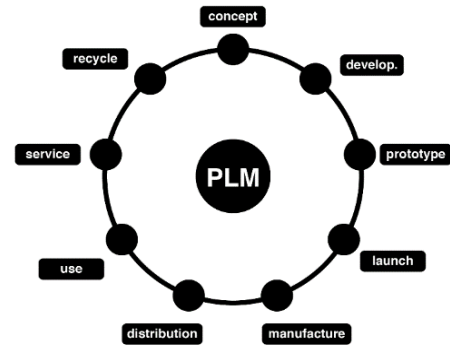
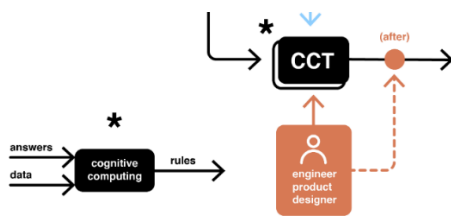*Figure 92 Product Lifecycle Management Conventional*
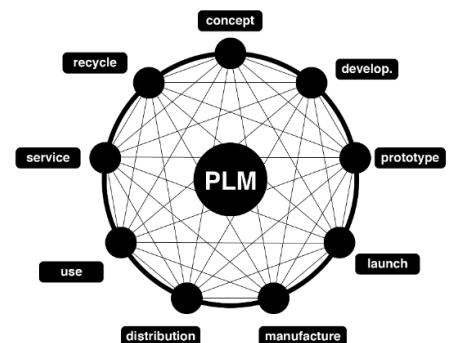
Figure 93 Product Lifecycle Management in Industry 4.0

5.1.2 Product Development Cycle and Cognitive Computing Tools

The next logical step shall be the implementation of the two verified missing and tested features: Cognitive Computing Tools (CCT) in the Product Development Cycle (PDC) *(Figure 94)*.
Following the project guidelines, experiments and conclusions: not only is that implementation possible, but necessary and inevitable. With that being the only way of the Product Lifecycle Management PLM cycle being fully recursive: the natural outcome from the recent contextual developments.

For the first, the PDC element represents the early stages in the PLM: ideas and concepts validations. The urgency and utility of developing tools for such stage were already pointed out: the costs and time can be reduced dramatically and the efficiency equally improved by targeting that phase and connecting the information to the rest of the scheme.

Figure 94 Cognitive Tools in Product Development Cycle

As for the CCT, they will help mitigate subjectivity when it's neither needed nor beneficial. Most methodologies and tools used in the development phases might try to minimize subjectivity by implementing standardized set of criteria and evaluation, the reality is that human evaluation is always highly subjective and biased.
Recognizing its effectiveness, complementing this set of established methodologies with CCT-based recommendation systems directly into the development phase will give a richer and more reliable approach to product concept evaluation.

Those tools shall never entirely replace the human intervention and subjectiveness, as those are always needed. For that to happen, tools and methodologies have always to regard the degree of influenceability of those. More: even that degree of integration can be expressed and worked through mathematical and algorithmic expressions, in the same objective fashion. The timing, degree and typology of that influence is key to understand how biased the creative and creation work is.

5.1.3 Changes and Risks

The implementation of Cognitive Computing Tools (CCT) tools will imply some significant changes in the PLM scheme of things. With that in mind, the Product Design Engineer (PDEng) role and relative position to that scheme will logically suffer considerable changes derived from those actions.

That it is due to its conceptual framework being totally different from the previous made tools: — not only in their usage, but also in the way they are created, interpreted and implemented *(Figure 95, Figure 96)*. This will ultimately deliver the decisive answer to the previously posed questions:

- What are those changes?
- How much (radical) change will they presume?
- Which kind of risks and new skills will be required?
- Will it be possible for the Product Design Engineer to maintain its "professional integrity"?

To answer those questions, one has to analyze the visual changes explicit in the PLM scheme. There are three major changes that can be individually identified.

The first one is the change of the accessibility paradigm from both the learning curve reduction and decentralization of the frameworks. The second one being the interdisciplinary communication coordination: all data processing, interpretation will be automatically inter-exchanged and translated for the an universal inclusivity of disciplines. Lastly, the third one is a shift of focus of work and interpretation: from the input to the output. The shift to cognitive-based tools will presume this shift with.

For each one there is a set of risk factors and considerations that one should have. Those will be explicated in the next pages.
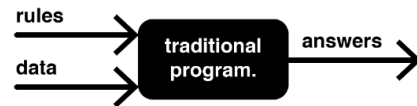
Figure 95 Traditional Programming
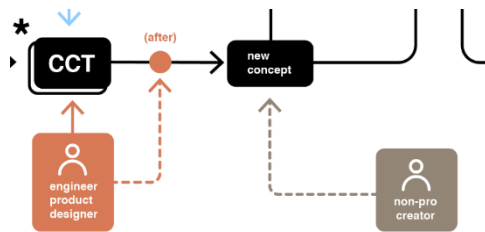

Figure 96 Cognitive Computing

Figure 97 Non-Professionals Inclusion

a. Cognitive in the Product Development Lifecycle: Accessibility to Non-Professionals

The first consequence of the changes that the Product Design Engineering will undergo is the increasing accessibility to non-professionals *(Figure 97)*. It is important to define some facts and definitions for some of the concepts mentioned. For first, this tendency is not exclusive from these implementations: PDE and other creation and creative disciplines have an increasing flow of people that are manifestly non-professionals. A second point should address the definition of non-professionals: from some assumed criteria, they should be considered the ones that do not hold academic degree in this area, or not sufficient experience. Of course, this definition has huge ambiguity issues, specially for the latter, but it is crucial to define some "common-ground".

The tools will become more accessible due to its reduced learning curve — as they'll be more intuitive and user-friendly —, and they'll also be decentralized — meaning that anyone can access them anytime and anywhere.

From that, the more accessible and intuitive tools might require verification systems that should translate and verify the work produced by those non-professionals. Because the *raison d'être* of this tools is to reduce subjectivity and allow the users to focus in some other important tasks, it will become even more inviting and prone to include also non-professionals. That is not a "problem", but has to be considered because it will aggravate some issues that already exist today.

This issue ultimately concerns directly the professional integrity and identity of the Product Design Engineer. This is easily avoidable for the professional has the structure and specific know-how, for one. And the educational system should also follow and change its focus that will allow him to preserve that identity. The risks are:

- Accessibility: quality and not quality
- Loss of standards
- Too much reliance on such tools.
- Uniformization of results.
- The "Black Box" issue;

b. Interdisciplinary Communication Automatized: Between Specialties and Product Lifecycle Management Stages

The paradigm of the "4.0" is highly correlated with the interconnectivity of things. That includes people, teams and all departments.

The diversity of those that are implied in the Product Lifecycle Management scheme of things is immense. Despite of all the development made with communication technology, there is still very much entropy and misunderstanding between teams.

The Cognitive Computing Tools come to appease that issue — because if it is, it is not totally solvable with this current approach. This automatization of the communication translation produced by each group is the pivotal factor for the mitigation of this huge problem in big complex projects. By integrating embedded systems into one single decoding language for one and by designing translating frameworks systems for once, is the key-feature that CCT have that will allow such thing in a much more radical way than ever before.

These tools will provide a constant feedback and translation about the product(ion)s states and all the misconceptions, misunderstanding that are generated by the middle communication man shall be ceased. The "middle-man" won't be abruptly and simply cease to exist. This transition and even some type of tasks and business will still need this actor for either inputting, interpret or registering the generated information. Obviously, its number will reduce. As for the risks, they are:

- Misunderstandings
- No control of intermediary information exchange
- The "Black Box" issue;

c. Cognitive Tools Focus Shift: Interpretation and Tuning Specialization

The last major change is the workflow and interaction with the body of work change. The introduction of the cognitive-based tools and frameworks will imply that Product Design Engineers shall change its center of focus: instead of arbitrarily deploying methodologies — as it still happens with conventional tools and frameworks —, it will rather input the already modulated data (from some dataset) that will provide the information upon which the system shall adapt.

That process of adaptation can be integrally controlled by any actor that holds analytical skills — that can also be the Product Design Engineer. The level and focus of control will be in the tool "itself" — having already a previously designed interface for that interaction and tweaking, the Data Analyst can iterate through the best possible settings —, and also in the results themselves — being the measurement criteria for the latter.

An important note being that the mentioned "conventional tools and frameworks" are not to be excluded: — they still are as essential to the PDE's doing. The same for the human intervention: again, this tools and frameworks serve to "connect" more than automatize. Connecting the streams of data into a unified algorithmic translator shall make room for the Product Design Engineer to concentrate in other tasks — and ultimately emphasize its indispensability.

The transition on which this tools are to be integrated — specially for this characteristic —, should be the most progressive and careful as possible. The level of influence and the results' origin are not always clear. With that in mind, the level of influence is equally not always clear. The risks from that characteristic should be attended:

- Over-dependence in the tools;
- Over-uniformization;
- Decision bias;
- Quantity over quality and human input;
- The "Black Box" issue;

5.1.3 Elementary Questions for Future Endeavors

From the previous risk pinpointing, the next rhetoric discourse is naturally the answer to the question: what can the Product Design Engineer to preserve its profession? The depth of the moral/ethic dimension surrounding those type of questions can only increase in a dramatic fashion when such paradigm-shifting proposals occur. Nevertheless and recapitulating:

1. How should one prevent the misusage — if that statement even makes sense —, of such tools? And, with that broader competition;
2. How can a professional distinguish himself from the rest of the non-professional community
3. How one addresses future expectable issues like Privacy, Security and the "Black Box" issue?

As for more philosophical and existential questions:

1. Is that conservation possible? At what extent?
2. One should expect it? Is it beneficial?
3. How deep will be the change in the sense of compromising the whole profession?

Those questions will serve as "basic-checkers" for any future development and endeavors related to such tools and frameworks. Answering these questions will help prevent the aforementioned risks from happening — being only complementary: additional adaptation actions are always needed.

Previous sections pinpointed the main groups and changes typologies that shall occur in a near future when this type of tools and frameworks begin to be used in Product Design Engineering.

To help address those issue groups there will be two main categories of the future challenges: the first regarding the (levels of) interaction with the tools and frameworks; the second the specific trait that should be conserved and stresses for both academic and professional institutions.

a. Type of Interaction with Tools

The main shift will be that the center of its focus will be (not exclusively) in the development and specification of new libraries, frameworks, algorithms and tools. That means that the development of artifacts will occur simultaneously with the tools and that the product system should be translated into that framework — that being where the more holistic and generic skills of the Product Design Engineer come into use: interpret data, scalability, cooperation and optimization.

In sum, the type of interaction with the tools and frameworks will be distinct from ones from the non-professionals. Two major actions explain that: first for the project and context — integrated team, resources, institution —, are expectably bigger and more complex from the ones available to the non-professionals. The professional background is also expectably more complete and coherent. Despite of the need of some reeducation of the academic and professional institutions in that regard, it will be sufficient by itself.

Henceforth, for the first statement, the interaction with the tools will be completely different: for one, the PDE can delegate and support its decisions according to the institution, as the non-professional is constrained by the tools' availability that are already pre-made. Not only the tools tuning will be customized — also the complexity of the "response". The Product Design Engineer will have a different level of internal and contextual resources that should by themselves put him in another level.

The availability of the tools will be much more customized and optimized for the Product Design Engineer — that can already be seen in some major successful tool implementations such as the "fast.ai". There will be at least 2 levels of "complexity": one a broader public audience and other circumscribed and adapted for the Product Design Engineering world.

With the right adaptability and progression — by changing its focus and base its approach on that personalized response —, the Product Design Engineer shall safeguard its position in and from the present scheme of things.

b. Emotional and Interpretation Skills

As suggested previously, the Product Design Engineer is expected to develop — along with its academic and enterprise context —, some distinctive skills and capabilities.

- Emotional skills: the integration and for some reemergence of creative and creation skills are a simple consequence of the focus change;
- Integration skills: the ability to flexibly integrate and adapt processes and manufacturing is both distinctive but valuable in the industry;
- Analytical skills: a more mathematical and algorithmic approach to problem-solving is decisive for decision making and successful work;
- Induction skills: dealing with uncertainty will reach different heights with the introduction of this tools, as not everything is "down-to-earth".

With the process and inter-communication automatization, the Product Design Engineer shall have more time to focus to develop new skills *(Coussins, 2019)*. The cooperation, integration and collaboration skills will play a major role for the successful implementation of these tools, but also for the success of the Product Design Engineer profession.

One of the reemergence and distinctive skills in the emotional skillset of a Product Design Engineer is certainly drawing: — it represents the essence of the profession, still. It is the most immediate connection to the doing in an emotional sense. This skill is forever relevant in creative and creation professions. That and other skills will become ever more valuable as they're rare and/or demanded; and for the above mentioned reasons, at least the latter will happen. The subjectiveness shall always exist, but only where it is needed. Those fundamental blocks, statements and questions shall be omnipresent when considering the implementation and integration of this type of tools into the Product Design Engineer workflow.

This works is finally represented by one final scheme that encompasses all those elementary changes *(Figure 98)*.
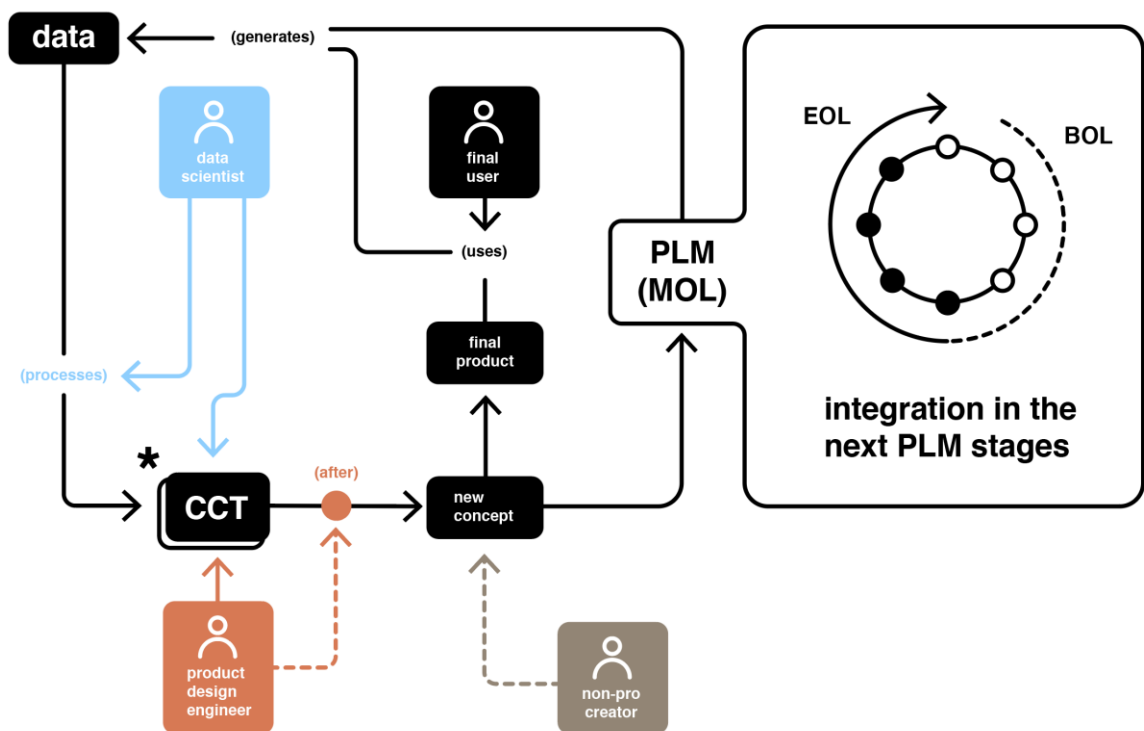
Figure 98 Final Scheme

5.4 Conclusion and Future Developments

The conclusion is that the Product Design Engineer should and will be able to preserve its role and position — that being ultimately beneficial to the Industry 4.0. Moreover its importance will rise with the reinforcement of the more specialized and emotional skill set.

This is achieved by considering the main schematic changes, addressing the issues and adapting the new skill set for this new role: all represented in the previous chapters.

The tools not only will be integrated in Product Development Cycle, but they will connect seemingly the next phases of the Product Lifecycle Management. It will make it a circular, closed and recursive loop of interconnected generation and interpretation of information.

The Lean concepts — not necessarily the one applied to manufacturing, from Toyota —, had a deep influence over this work. The same high levels of uncertainty that are present in innovational environments in big companies and startups *(Ries, 2011)* are the same present in the early stages of Product Management Cycle. The future belongs to the tools and frameworks that help explain the successful "leaps of faith" and "hypothesis" (that have to be) formulated by both innovation and early development.

For the future techniques and frameworks development prediction there are some contenders to be the next "big thing": Geometric Deep Learning being the most relevant niche of Deep Learning that might be relatable with Product Design Engineering. It is an alternative to the conventional bidimensional and Euclidean dimension of datasets. Noting that many fields may get a more convenient representation of their work into non-Euclidean models — such as 3D modeling and Computer Graphics —, into graphs and manifolds *(Figure 99)*. The true tridimensional understanding of digital representations, possibly leading to revolutionary applications in the years to come.
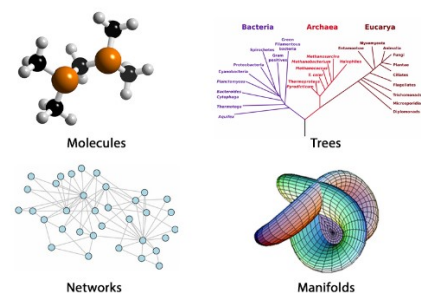

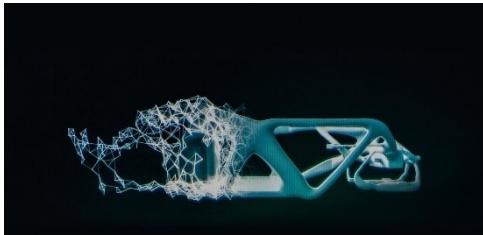*Figure 99 Geometric Deep Learning (Source:* Medium*)*

Figure 100 TEDx AI Developments (Source: TED YouTube)

Starting now in a broader scope: a conference held on TED, in a Dreamcatcher related talk, Maurice Conte forecasts that the products shall have a "nervous system" that allows them to collect data on the go — like a "nervous system": — and that being fundamental for the aforementioned applicability of the cognitive based tools *(Figure 100) (Conti, 2017)*. It is rather interesting the way he puts things: "the ability of products to give feedback about their usage". Undeniably, that should be the next great step: the enclosure and somehow funneling of the way we collect, interpret data and, consequently, design and engineer products from top-bottom. When the engineered product in its integrity becomes "smart", or when the material itself becomes smart — the Cognitive Material *(Noor, 2017)*.

Example of that is some of the recent literature that regards the field Engineered Living Materials (ELM) *(Bextine, 2017)*, where concepts such as "biological programmed and self-morphable materials" seems possible in a not so distant future *(Gilbert and Ellis, 2019)*. As of now that frontier is being blurred with "biological circuits" and the creation of programming languages that manipulate the construction blocks for biological and living materials: DNA *(Zimmerman, 2019)*. At the same time, the computation power is about to attain a new milestone with the new Quantum Supremacy acclaimed by Google — might not be long until we have a fully functional Quantum Computer unveil its true algorithmic potential *(Rieffel, 2019)* with the increasing computational power brought by that paradigm change essentially the logic that wraps the cognitive-based algorithms today.

The frontier between the digital and the physical can in fact become even more blurred — specially with the paradigm shift in algorithm creation. If all of those things happen, perhaps the resurrection of old terminology such as Ubiquitous Computing might be a possibility — where computation can appear anytime, anywhere. The possibilities are numerous.

Finally, one of the underlying suggestion theories from this document is that human subjectiveness shall be reduced in PDE — namely in Aesthetics. It is unexplainable that Aesthetics remains a well of mysteries when, in fact, very little is actually given to ambiguous criteria: — Design can have a stronger scientific basis; the only question being "at what degree?". That basis on which some Design starts or ends always follows the same set of rules — and those, that sense of beauty, are deeply imbued into our (in)conscient cognitive interpretation system *(Danko-McGhee, 2010)*.

There will always be a need for human contribution and verification, specially concerning creative(ion) areas. The tools will serve to augment human capabilities and efforts, not to fully replace them. (Only) humans can design (for humans).

True progress seems to often come from the fusion or interchangeability of two or more initially disparate disciplines. The degree of success in that merging it is directly correlated with the prominence of that new paradigm.

With automatization and technology, everything will require less human intervention and resources. Adding to that, the subjectiveness where it is not needed. Despite all that, right now it is simply not possible to segregate human intervention in general creation: and as technology develops, its value rises with its rareness, as it brings also distinctiveness.

We are living in fascinating times.

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