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Coevolution of digitalisation, organisations and Product Development Cycle

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Over the past 70 years, product design has undergone many important changes due to the impact of contemporary digital technologies (i.e. digital design). To support digital design and information flow throughout the product lifecycle, the digital-driven technologies currently in use rely on the evolution of CAD and PLM systems to address new design and manufacturing challenges generated by the new era of 4.0 digital transformation.
This paper will discuss the past and present coevolution and shortcomings within industrial organisations, the digital technologies employed in the product development cycle and will illustrate the current challenges and future prospects of the digital thread for design.

Computer Aided Design (CAD); Design; Digital Transformation

1. Introduction

Product (i.e. system) design has been a visionary, creative and modelling activity since the Renaissance period when artists, like Leonardo Da Vinci, provided the first sketches for systems such as helicopters [1]. Throughout this period, progress has created a more standardised Product[1] Development Cycle (PDC), which not only includes many more stakeholders, but also takes into account the entire product lifecycle and provides opportunities and methods for innovation, knowledge management, etc. [2]. The systems themselves have also evolved over the four industrial periods/revolutions: the mechanical systems are currently coupled with electronics and computing algorithms, and are connected to the digital cloud. Here are the Cyber Physical systems [3]. Although product development has been an intellectual activity for many years (with sketches, 2D drawing, 3D modelling and process planning…), the third industrial revolution, which brought forth the rise in computing technology development, has provided new digital support for the PDC since the middle of the 20th century [4] [5] [6]. Since then, both the PDC and digitalisation have undergone and will undergo many changes[7], [8].

In parallel to the developments in the PDC, studies were, and are continuing to be, carried out on the advances and efficiency within the industry [9]. In 1982 some models were presented, bringing to the forefront certain key points that would be the focus of following sections: “industry governed by the interaction of changes in technologies and prices over time” [10].

So, are the previous, current and future changes better for product development (functions, technologies, services) and performances (energy consumption, lifespan)? Are they more efficient (development lead time, time to market, cost reduction, etc.)? Are they better for humans and society (working situation, environmental impact…)? What drivers have been responsible for these developments, and what drivers could/should be implemented in future advances?

1.1. Topic and Scope

The objective of this keynote paper is thus to discuss the continuous changes that have taken place over time. The given/proposed drivers may then provide insights for academics and manufacturing industries that will help them with their teaching content, the Product Development Cycle and the related IT support developments, thus moving towards a stronger alignment in the future. In order to present this coevolution and mutual development, the scope of this paper will cover the three pillars of growth, perceived as fundamental and linked for product engineering processes:

- The PDC (process and knowledge-based set of activities),
- Human and organisations (the PDC’s fundamental resource),
- Digitalisation (one of the continual developing key IT resources that supports the PDC activities: modelling, validation …).

Coevolution between organisations and industrial changes has been studied from an economic point of view[11]. Two development strategies, based on technologies and governance, have been put forward [12]. Hence, the objective of this present paper is to give an insight from an ‘engineering design’ perspective questioning the development impacts among PDC, organisations and digitalisation. Without prejudging any completeness, the authors have decided to study these three pillars, the collateral impacts of which have been strongly perceived over the past 30 years.

The paper will describe and discuss how design methods, models and digitalisation were primarily developed so as to provide strong support for design activities. Following this, the recent digital developments coupled with increasing processes and product complexity will be discussed with regard to the fundaments of the PDC, the future expectations of the

[1] Here, the authors use the term ‘Product’ for both ‘Product’ and ‘System’ definitions. Some explanations of the difference between the two words can be found in references [202], but the difference is not significant with regard to this paper. Both ‘Product’ and ‘System” implicitly take into account ‘Product Complexity’ characteristics.

population/society confronted by new technologies and services, and global expectations for the planet.

Subsequently, these three pillars will be expected to mutually evolve in twinned continuous mode. However, the question is, can this be deemed a reality or just an expectation?

1.2. Overview of the study and discussion

Fig. 1 illustrates the keynote principles that:

- Provide a synthesis of the relationship between the PDC, organisation (tasks, roles and skills) and digital support. The paper will also examine how scientific research and software developments have somewhat fallen out of alignment.
- Portray the coevolution and disruption of the three pillars over the years and demonstrate the current interest in a real dual push/pull approach for future developments of both industrial and IT developers and vendor practices.

Three practices (time periods) illustrate the main evolution.

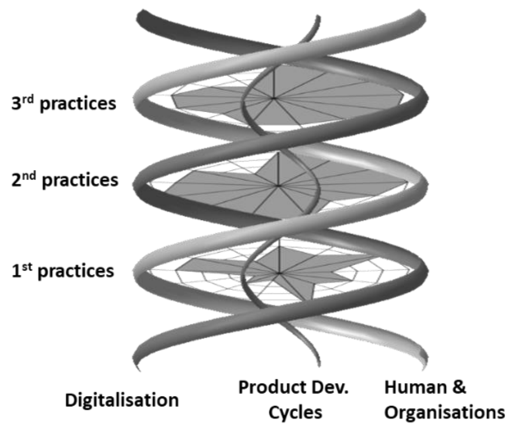

Fig. 1. Illustration showing the evolution of a PDC, Human & Organisation and digitalisation.

The representation of this mutual evolution is represented by a DNA-like metaphor. The DNA means that twinned relations should exist among the pillars as since the evolution of one impact the two others. They drive the overall behaviour of engineering design evolutions.

The three pillars have been characterised using several attributes described in Table 1. They will be represented in the following sections on a radar graph in order to show the increasing maturity of design concepts, digitalisation solutions and organisation over time (Fig. 5, Fig. 7, Fig. 11).

The last three characteristics depict the mutual influence (i.e. coevolution) of the three pillars. These characteristics are the focus for this paper as they highlight the brakes and drifts of what could be the values of indicators for the ideal mutual development of PDCs, digitalisation and organisation. They are used, in section 6, to discuss what could be a future investigation roadmap in the academic community.

As no metrics exist for the time being, the majority of the characteristics is currently qualitatively assessed. Nevertheless, the key trends presented in the paper are given prominence and supported by scientific literature. A qualitative five-level scale is used. The paper does not provide any scientific justification of those levels. Nevertheless, that will also be discussed as future work for the academic community (see section 6).

Product Design Cycle	
System complexity	How complex the manufactured output of the PDC is?
LC coverage	How the PDC incorporates all the information, processes, and stakeholders, of the product's entire lifecycle?
Digitalisation	
Auth. Apps	Is the digital application an authoring application (Yes/No)?
Manag. Apps	Is the digital application a management application (Yes/No)?
Product behaviours Fidelity	How accurate is the fidelity of the models face to real system behaviours?
Engineering features fidelity	What is the level of dependability for an ad equation with fundamental engineering functions (modelling, capitalisation, integration, change management…)?
TRL	What is the TRL of a digital application?
Organisation	
Indiv. / Collab. for PDC tasks	Is the Design organisation collective or individual?
Synch. / Asynch.	Is the Design organisation synchronous or asynchronous?
Internal / Extended business model	Is the Design organisation developed as an internal or extended business model for manpower, know-how, subcontractors?
Coevolution	
TARL	Technology Acculturation level
CARL	Concept Acculturation level
PDC drive ability	How design concepts drive digital development

Table. 1. Definition of the characteristics that represent the development of the three pillars over time.

1.3. Organisation and outline of the paper

This paper is divided into seven sections, and will develop through four temporal practices (sections 2-5, Fig. 2) chosen by the authors as significant regarding engineering design evolution: IT appearance, globalisation of industry, industry 4.0 trigger, future prospects. As illustrated, practices are not stopped when the following ones appear. The benefits of each are summed. The overlapping expresses that maturity always grows. The areas of progressive radar graphs never decrease. Section 6 finally will draw some topics for a scientific roadmap in engineering design.

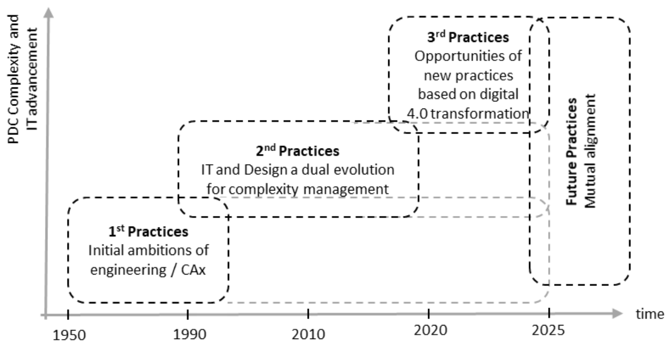

Fig. 2. Time line of the main coevolution between the PDC, digitalisation and organisation.

The *first practices* were established in the 1950s and continued through to the early 2000s (Fig. 3). They provided the fundaments that generated the interest in IT developments and highlighted the benefits that would arise from the tasks, roles and skills in the system development process. They also outlined what was hoped for from IT solutions, concluding that there was a certain independency between IT solutions and design concerns (partial implementation). Due to the continual advances in design methods (System Engineering, Design for Additive Manufacturing), this parallel development remained of great interest in that it supported simple tasks more quickly (assistive tasks).

The *second practices* demonstrated how the significant developments in computing technologies (1990 – 2017) and calculation capacities were leading factors in the evolution of the Internet, CAD, PLM, cloud services, etc. At the same time, industry became global (extended enterprise, supply chain…). Thus, this section will highlight how engineering tasks, roles and skills, and IT benefitted from each other, thereby supporting the system, organisation and digital complexities (Product Lifecycle Management & collaboration, Knowledge Management/Artificial Intelligence & industrial best practices, CAE & behaviour extrapolations….), although the match/fit between IT solutions for engineering and engineering functions was still being questioned. This section will thus depict the basic engineering features versus the implemented features and the relationship between manufacturing industries and software vendors.

The *third (new) practices* have been maintaining the relationship between engineering and IT, as presented in sections 1 and 2, portraying the evolution within the new industrial revolution called Industry 4.0 from 2017 to the present time. The section analyses whether technologies 4.0 (AI, cloud, VR/AR, etc.) provides better opportunities for industry with regard to new coevolution meeting engineering requirements (e.g. digital twin, MBSE, computational design analysis). This analysis is based on an enumeration of performance indicators /values that are used to assess engineering and IT performances (robustness, flexibility, human acceptability) in order to drive the future developments.

F*uture practices* will finally provide a theoretical model of the future of engineering and IT solutions based on a global synthesis of the coevolution of engineering and IT solutions that is the main focus of the paper. This section will give prospective to consider how engineering activities, organisation and digitalisation will evolve with regard to the future generations' expectations. This prospective will appear in three scenarios that take into account technological advances, innovation and user experiences. The study therefore concerns the coevolution of Product, System, Services, Software tools, Methods / social and societal visions (data should remain a support for humans) / environmental aspects (how IT solutions are sustainable).

In each of the four sections, transversal analysis will be applied to the corresponding practices: 1/academic and industrial training approaches with regard to design and digital transformation, 2/ assessing the digital transformation using either the alignment of the three pillars analysis, or the Return on Investment analysis that should indicate how the investment balance benefits industrial performances.

The sections will provide research results, state-of-the-art reviews, the authors' objectives, debates and perspectives so as to give academics and manufacturing industries key information on which they will be able to base their expectations and perspectives for future developments.

2. First practices: initial engineering objectives / CAx

2.1. The rise of Computer-Aided Design

2.1.1. Historical background

In the 1950s, the potential use of computers to support the engineering design process came from gaining numerical control of machine tools [13], [14] and the first computer systems through graphic interfaces [15], [16]. Accommodating engineering design processes with these new technologies was an important challenge for industry and academic research motivated by the development of efficient communication between the designer and the machine. Ivan Sutherland's MIT doctoral thesis "Sketchpad: A man-machine graphical communication system" is recognised as the first important contribution towards the development of assistive systems for engineering design [17]. Although a large number of applications and developments focused on computer graphics applications and the implementation of technical drawing along with shape representation using computers [18], [19], the objective of Computer-Aided Design was to help with the development of machine systems that enabled the human designer and computer to work together on creative design problems [20]. In contrast to previous computer applications, which were batch-oriented, thus time consuming and without any intermediate intervention, the interactivity between man and machine provided by Computer-Aided Design was a major technological advance in design and engineering offices [21].

In the early 1960s, despite the emergence of the very first computer systems with a graphical interface, computer software and hardware were in their infancy. It took a decade for significant changes to occur that resulted in the reduction in the size of mainstream computers, the development of micro-computers with increasingly better performances and advances in programming languages from assemblers right through object-orientation thus leading to a new generation of user-friendly CAD systems [22], [23]. In spite of all these achievements and significant developments in Finite Element Analysis (FEA) and Numerical Control (NC) manufacturing, these assistive systems could only process basic geometric shapes, which further isolated Computer-Aided Design from downstream applications.

2.1.2. Geometric Modelling: from shapes to solids

Geometric modelling in mechanical engineering and the development of Computer Aided Design provided a fundamental role for the geometric description of shape in the design process. Shape was mainly used as a multidimensional medium characterised primarily by its geometric or spatial reach in a space with one, two, three or more dimensions [25].

Although Euclid's geometry and Plato's solids were the premises of a general theory of shapes, it was not until D'Arcy's pioneering work that a study on the mathematical characterisation of shapes was carried out [26]. On the basis of his work, Kendall [27], [28] put forward a definition of shape that become the de facto reference in different research domains "shape is all the geometrical information that remains when location, scale, and rotational effects are filtered out from an object".

Requicha's [29] work on the foundations of solid modelling highlighted the role of computerised shape representation in capturing geometric aspects and their exploitation in modelling and simulation in engineering [30], [31].

As a result of Requicha's work, shape modelling in mechanical engineering evolved by applying mathematical and computer models for curves, surfaces and solids [32]. By conceptualising the real object or part, Requicha was able to define three levels of abstraction. The first level enabled the object to be modelled defined and specified (physical universe); the second level made it possible for the object in question and its properties to be mathematically devised (mathematical universe); the third level provided the representation schemes of the mathematical objects with a representational system (representation universe). A fourth universe that would translate the representation universe into data and structures for computer languages was put forward by a number of researchers (implementation universe) [33].

Consequently, the representation of shapes and solids benefitted from theoretical characteristics and algorithmic developments from the different disciplines of pure and applied mathematics and computer science. Without being exhaustive, the representation of shapes in mechanical engineering can be categorised into discrete and continuous representations and consider elementary structures as the basis of the representations (point, mesh, curve, surface, volume).

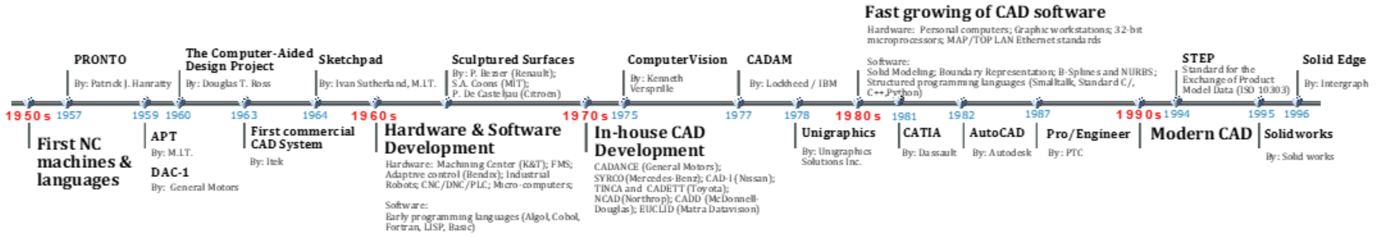

Fig. 3. Computer-Aided Design time line, adapted from [24].

2.1.3. Solid Modelling

Solid modelling encompasses the entire set of mathematical and computational principles for the digital representation of 3D rigid object shapes [29], [32]. Solid modelling has evolved over the last thirty years and has widely contributed to solid modellers of CAD systems providing computational solutions for the design, processing, visualisation, exchange, and archiving of parts and assemblies.

The main issues of solid modelling are the theoretical foundations, the representations of geometry and topology, algorithms, systems and applications. However, it differs from other areas of geometric modelling in that if focuses more on the completeness, accuracy, and fidelity of the physical object as well as the universality of representations and algorithms [34].

Thus, in solid modelling, any representation must be unambiguous and correspond to physical and real objects. However, above all they must allow for queries and geometric processing that can be applied to the corresponding physical object.

The first models used in CAD, called "Wireframes", were defined by vertices and edges (wires) joining them. Other representations were developed, such as four-edged faces, and were extended to freeform multi-sided faces with increasing complexity. However, these models had limited visualisation capabilities and with very poor semantics, it was not possible to represent complex surfaces and query the relevant properties of the solids.

More sophisticated solid representation schemes were developed in the mid-1970s and the early 1980s [35]. Many researchers in the US [36], [37], the UK [38], Japan [39]–[41], Germany [42]–[44] ,and France [34] developed the Constructive Solid Geometry (CSG) model so as to build solids using primitive shapes such as cubes, cylinders and cones, along with Boolean operations (intersection, addition, and subtraction) to combine these basic elements. These achievements provided the basis for a number of academic and commercial systems such as EUCLID [35], COMPAC [44], PADL [47] [48], PROREN [42] and TIPS [49]. In the meantime, the Boundary Representation (BRep) for solid models was masterminded by Baumgart and Braid [50], [51] and used a face-edge-vertex data structure and Euler's operators to describe the solid using a (2D) surface boundary that enclosed the solid. CSG and BRep greatly influenced CAD development in the early 1980s [52], [53]. The requirements of these representation systems were also formalised in terms of domain, validity, completeness, uniqueness, conciseness, ease of creation, and efficacy with regard to applications [29].

2.1.4. Curves and Surfaces for CAD

The development of mathematical models for curves and surfaces in the first CAD systems was greatly motivated by the challenge of manufacturing complex or freeform shapes in the aeronautics and automotive industries. The pioneering studies conducted by Coons (Ford) [54], Bézier (Renault) [55], De Casteljau (Citroën) [56] and others still remain the foundation of today's CAD systems. Their main idea was to approximate sculptured surfaces as a collection of finite surface patches expressed in terms of parametric surfaces piloted by control points and blending functions. The main benefit of Bezier curves and surfaces was the ease of controlling the shape on both the inside as well as on the boundaries [57]. However, their applicability was restricted when dealing with conic sections, global control and the number of control points, which considerably complexified computations. With regard to spline curves [58], De Boor and Cox [59], [60] introduced B-Splines as a generalisation of Bezier curves and surfaces, whose properties included continuity at the joints and an absence of dependence on the number of control points. Versprille's NURBS (Non-Uniform Rational B-Splines) invention [61] enabled a wide spectrum of surfaces, such as revolute, extruded and ruled surfaces [62]to be modelled.

Today, NURBS have become the standard curves and surfaces for CAD due to their simple representation, although many computational problems with NURBS, such as intersection, merging, blending, etc. [63], still remain.

For many years, research on surfaces evolved independently from those on solids. The research community on CAD addressed two major problems using very different methods ("data structures" for solids and "applied mathematics" for surfaces). However, the difference in the approaches were not without consequences, which resulted from the difficulties encountered in combining surfaces and solids in a unified model. This merging of the two was one of the most important issues for CAD in the 1980s [64]. Moreover, CAD systems faced significant criticism from designers who reported difficulties in using them, and it was not until the introduction of feature-based and parametric CAD that this reluctance started receding.

2.1.5. Parametric modelling and feature-based CAD systems

Feature modelling can be considered an extension of geometric modelling [65], [66]. However, unlike geometric modelling, which contains only basic geometric information, feature-based modelling was enriched with semantic data and encapsulated attributes, parameters, and constraints [67] [68], [69]. Geometric features were mainly used to define a feature's shape and served as the basis of designing-by-features in CAD systems. However, geometric or form features did not convey functional aspects [70]. Feature-based approaches in design evolved and led to feature models driven by specific contexts [71] such as function [70], [72] assembly [73], tolerancing [74], and more integration with process planning [75] and FEA [76].

Feature-based systems relied on generic feature libraries that contains predefined features such as holes, bosses and slots and operations to edit and modify the related parameters [77], [78]. These parameters could be used to define relationships and constraints intrinsic to the geometric features or between different features and geometric elements [79].

Parametric modelling in CAD inherited algorithmic thinking, derived from parametric design, to solve design problems based on translating the relationships between internal and external variables affecting the design elements into parameters [80], [81]. Parametric modelling is fully associative and benefitted from the development of object-oriented programming and variational geometry [66], [82], [83].

Feature-based parametric modelling was considered an important milestone in the development of CAD systems towards procedural history-based modelling in CAD [84], [85] (Fig. 4). This new technology positioned the PTC Company with Pro/ENGINEER software as a leader in the CAD industry up until the mid-1990s.

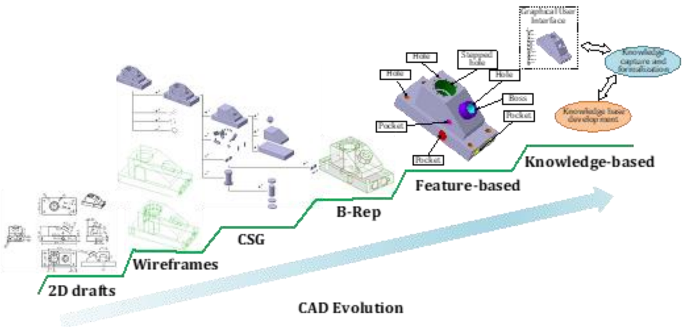

Fig. 4. Evolution of CAD models and representations, adapted from [86]–[88].

2.1.6. Data Exchange and Interoperability

Although the CAD world in the late 1970s was dominated by a few industrial CAD systems, the need to exchange data files between different CAD systems and downstream applications such as analysis and manufacturing stimulated the development of new standardised formats for data exchange. In the 1980s, the Initial Graphics Exchange Specifications (IGES) format was developed under the auspices of the ANSI Y14.26 Committee to facilitate the exchange of geometric and non-geometric data conveyed by curve and surface models as well as solid models [89], [90]. In spite of its success, industrial applications revealed many shortcomings regarding file size, processing time, numerical sensitivity, and the concentration on the transfer of data rather than information [91], [92]. In 1984, the Product Data Exchange Specification (PDES) project was set up to counterbalance the IGES' weaknesses and served as the basis for an important international initiative under ISO/TC 184/SC 4 (industrial data) [92], [93]. This action led to the development of the Standard for the Exchange of Product model data (STEP) (ISO 10303) for an efficient exchange of product-related data between different CAD systems or between CAD and downstream applications [94]. The first parts of STEP were published in 1994 and STEP application protocol AP 203 superseded IGES for geometry data exchange [95].

2.2. CAD market

Thanks to all these fundamental developments, the sophistication of computer languages and the wide deployment of workstations and desktop PCs in the industry, CAD experienced considerable growth and there was a rapid expansion of the market [96] of which mechanical applications constituted the main part. It was in the aeronautics, automotive and shipbuilding industries where CAD was the most used and where it made the greatest progress. It is worth stressing that many of the developed systems originated from aviation companies such as Boeing, Lockheed, Mac Donnell Douglas, and Dassault Aviation [97], [98].

During the initial period of developing CAD systems, the CAD market was dominated by Computervision (CADDS) and IBM/Lockheed (CADAM), which provided turnkey solutions consisting in both software and hardware. By the mid-1980s and with the advent of powerful personal computers with new operating systems and the co-existence with workstations, the CAD market witnessed new players such as IBM-Dassault Systemes, EDS-Unigraphics, Autodesk, Parametric Technology and SDRC. By the end of the 1980s, half of the CAD market was in North America, 35% in Europe, 10% in Japan and 5% in other countries [99], [100], [101].

2.3. CAD training and education

As from the 1980s, training became a vital component of CAD deployment in industry. Three types of training were set up: awareness, initiation, and specialization. While the first two themes were dedicated to managerial functions, the third allowed for a wider diffusion and adoption of CAD tools in design and engineering offices. Despite the excessive cost of CAD software and hardware, companies spent large amounts of time and money on training in the hope of shortening the learning curve. It was clear that the introduction of CAD revolutionized the design process in companies, but it also changed the product design culture creating a new generation of designers and engineers separated from their mentors by this new technology [102].

With its increasing popularity in industry, CAD gained a prominent place in universities and schools as a training resource for future generations of engineers and product designers. However, the tools used in the education environment were not designed for teaching but rather for industrial use [103].

The main outcomes of adopting and implementing CAD technologies in product design education were the enhanced practices of generating engineering drawings with advanced representations using up-to-date standards, using computer-generated models to replace physical models for visualization, simulation and testing, integrating manufacturing and engineering data and information to allow for better communication between engineers, manufacturers and inspectors, and capturing design intent through feature modelling and parameterization [104].

The balance between teaching the fundamentals for theoretical understanding and using the software for design and engineering applications was also an important issue in the development of sound technical courses. Moreover, the lack of software and hardware standards hindered the broad deployment and sharing of education tools until standards were developed and consolidated[105].

2.4. CAD research

CAD research in design and manufacturing has undergone significant advances since the first CAD systems. With these systems being mainly developed by computer scientists and engineers, research in mechanical CAD adopted new methods and tools from computer science and information processing. Moreover, the cooperation between mechanical engineering and information-processing became crucial [106]. As design is an integral part of production and manufacturing systems, CAD research has been flourishing since the mid-1980s and particularly within the CIRP Design community. Spur and Krause [107] highlighted research problems in CAD in terms of user friendliness, design logic, geometric modelling, downstream applications for process planning and robotics, and methodologies for CAD. Peters and al. [108] drew attention to a computer approach to design by differentiating between the direct design activity for basic tasks such as drawing and the indirect design activity that required a fast, efficient and flexible use of information flow, friendliness, languages to support design methodology, standardisation and databases. Other research stressed the need of geometric fundamentals [109], product models [110], and coupling with FEA [111], CAPP [112] [113], [114], CAM [115], [116], [117], and inspection [118].

Research on the topics related to user friendliness, design intent modelling and conceptual design have enabled important achievements to be made. The development of programming languages and object-oriented modelling opened up communication channels between the designer and the CAD system [23]. The representation of the designer's intent benefitted from geometric reasoning mechanisms based on mapping design requirements to geometric constraints [119], [120]. Computer-aided conceptual design systems also benefitted from active research addressing the characteristics and requirements of conceptual designs for CAD [121], [122], [123].

Thus, the most significant research prospects during this first phase were related to information-driven CAD systems and product modelling for CAD. With the development of information processing technologies, CAD research witnessed a variety of efforts to transfer design methodologies to computers [124]–[126]. Moreover, dealing with functions over the geometry in the design process and interacting with other stages of the product lifecycle required more computational and cognitive approaches. Intelligent CAD (ICAD) [127], [128] had gained in popularity as a fundamental approach that facilitated decision making and enabled CAD/CAM integration [116].

AI techniques and knowledge engineering tools supplemented predicate logic and expert systems [129] so as to better understand the design process and design objects using design knowledge systems [130], [131], extraction of design information using knowledge rule base [132], implementation of computational design processes integrating descriptive and cognitive models [133], and representing functional knowledge [134] ,[135]. Hence, the concept of intelligent CAD was extended to the concept of "knowledge intensive engineering" [136] and also benefitted from feature representations and technologies [137] and product modelling [138].

Product modelling emerged as a comprehensive concept for capturing geometric data and semantic information during the product lifecycle [110]. The product model was understood as a logical aggregation of all product-related information throughout its life cycle and the link between a knowledge and data model [139]. With CAD, the developed product models were categorised as structural/geometrical models [140], functional models [134], [72], feature-based models [141], and domain-related models [142]. Product models gained from information modelling, and thus relied on the general structure of objects, relations and attributes [143]. Through their function-related, domain-specific and integration characteristics, feature-based product models proved to be very popular in CAD research [71], [144]–[148].

In addition, the area of tolerancing achieved through product modelling successful means to overcome the representation limits implied by solid modelling in CAD systems [32] with an adequate framework for functional tolerancing [149], integration with process planning [150] and the development of CAT (Computer-Aided Tolerancing) systems, thus supporting new tolerancing models [151]–[155].

2.5. Synthesis: promising and profitable support to be continued…

Through its early pioneers' vision, CAD was developed as an assistive interactive medium to support the entire product development process, from the conceptual to the detailed design phase (Fig. 5). During this initial period, CAD became ubiquitous in companies' design offices, driven by industrial demand in the aeronautics and automotive sectors and supported by significant mathematical and algorithmic developments. CAD thus proved to be an important asset for product design, strengthened by the emergence of new hardware and software solutions, and the rapid evolution of computing technologies [156]. Gradually, the integration of information processing technologies in product development allowed for considerable progress in dealing with routine activities, while the development of other digitalisation-related activities for design validation and production, such as CAE and CAM, were carried out in isolation, thus preventing effective integration with CAD [157].

Research was rather successful in facilitating the progress of digitalisation and the commencement of early coevolution [158] [159]. Still, several challenges remained in terms of the theoretical and geometrical foundations of CAD, robustness, data reuse, interoperability issues, lack of semantics and insufficient multi-disciplinary integration [160], [4]. In addition, the recommendation for the need for new interaction mechanisms such as alternative human computer interface (HCI) solutions was also raised by design theories and methodologies and in particular for conceptual design [161].

As stressed by J. Hatvany in "Dreams, Nightmares and Reality" [162] [163], CAD was inevitably expected to follow this historical cycle. However, the advent of new information technologies and artificial intelligence mitigated the development risks [164], [165] of handling data exploitation and collaborative work with the arrival of databases and the increase in Internet usage.

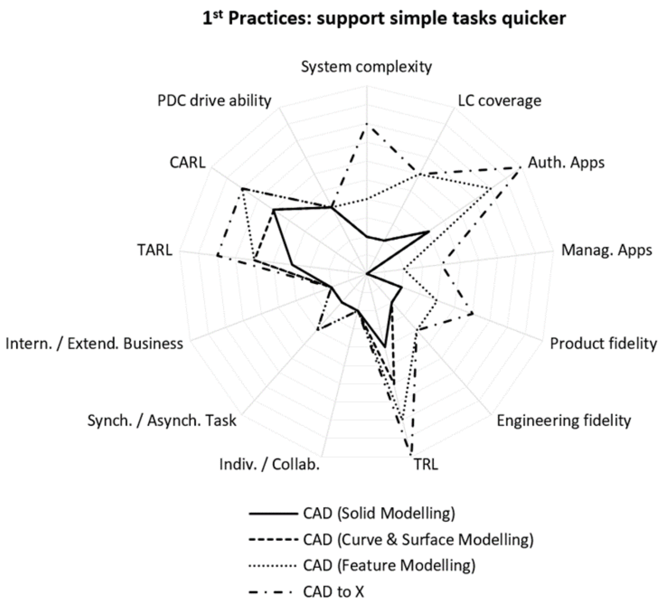

Fig. 5. Radar graph of 1st practices indicators.

3. Second practices: dual development of IT and Design for complexity management

3.1. Parallel Development of Engineering Design and Information Technology

As CAD tools developed into the 1990s, information technology developed in parallel. The internet started as a very simple decentralised information system and grew into a global IT platform of significant complexity [166]. Configuration management approaches, first practiced in the 1950s, became standardised within IT toolsets so that design could be split and merged at different times [167]. Database systems scaled across private networks, internet file systems, and, now, distributed computing and storage in the cloud. Workflow technology supported organised use of the internet and also allowed for guidance and enforcement of the best practices. Integration tools, middleware, and interoperability standards supported connected workflows across multiple generations and multiple implementations of design tools and databases.

CAD tools followed a similar trajectory for both small scale (SME) and global engineering organisations. Sophisticated representation and file systems allowed part designs, assemblies, and product hierarchy to be coordinated, organised, and available, minute-by-minute to multiple designers and engineers in the development cycle. Different tools emphasised parameterised models, point-set models, and manufacturing process models [168]. Eventually CAD technology advanced to the point that an aviary of modelling approaches could be used in unison. Feature-based modelling and design parameter databases offered standard ways to share, embed, and enforce the best engineering practices. Analytical tools coupled with the design environment supported engineers in their search for more innovative designs and quick validation to ensure that designs were functional and manufacturable. As the PDC progressed, configuration management allowed for design variants to be generated at many steps during the PDC [169].

Systems for product definition and lifecycle data evolved along the IT path; while sometimes rooted in engineering practices these systems were more often shaped by IT capabilities. Product data management tools matured following a number of different, often vertically separated, approaches. Bill of Material (BOM) systems supported the modelling of products, assemblies and parts so as to connect to industry standard databases. While once only available as part of very large-scale enterprise resources planning (ERP) systems, BOM systems became available for SMEs in very heterogeneous supply chains. Product Lifecycle Management (PLM), pioneered in the late 1980s and implemented at scale in the 1990s, served large-scale enterprises and managed design activities, manufacturing process information, and product performance over the lifecycle.

Advances in CAD and IT supported significant changes in industry practices. Earlier models of engineering design and development were based on isolated activities that were often passed from one functional area to another with little or no feedback or negotiation. Newer technology and design methods brought concurrent engineering, collaboration across functional areas and coordination among many different temporal or design stages [170].

Design activities also became more sophisticated. The information was that multiple designs came to be used for understanding classes of requirements, design approaches, and the mapping of functional requirements to design features and parameters. Later, this extended representation was also used to understand, via artificial intelligence, the relationships that could be used for design optimisation and new designs.

In this section, the paper will develop and question the keynote of the developments in software technologies and organisations that manifests a certain separation between these two developments. Key factors which, in the authors' opinion, are key elements of this separation.

3.2. Growing complexity of the manufacturing industry

Following the overview of the second phase in the development of information systems, the paper will then dwell in more detail on the increasing advances of complexity in the manufacturing industry. The analysis will be based on the definition of complexity as given by [171] as having many interactions between the elements of a system. Currently, this is still a real topic for engineering and manufacturing activity [172]. The paper will first examine the manufacturing industry's organisational system that includes embedded product development methods and models. Then it will put forward that the IT system is a set of interacting functionalities.

3.2.1. Complexity within the product development process

Until the 1980s, the engineering process consisted of all business activities mainly carried out sequentially in order to gradually transform the expected specifications of the product towards its detailed definition. At that time, [173] described this product development process as a four-phase process: requirement specification, conceptual design, embodied design and detailed design encompassing every CAD and CAx model that validated the selected materials, forms, manufacturing processes. Research was then carried out so as to understand how this multidisciplinary development process could be integrated into CAD solutions [174].

The 1980s then experienced the advances made in these industrial practices that nevertheless introduced concepts that are still used in current approaches today, albeit a change in vocabulary: requirements, system architecture, validation, etc. What initiated this major change was surely the change in the 'over the wall' paradigm towards that of 'collaboration' between each of the stakeholders involved in the development process [170]. Thus, these reflections laid the foundations for future changes in organisational practices for design process modelling, system complexity and the development of related information and data modelling. Theoretical concepts of PLM (Product Life Cycle Management) progressively took into account the stakeholders' needs in the system's life cycle during its development process [175] [176] [177]. The process was also studied and improved to provide more innovative and better products on the market (e.g. [178]). Following this, multiple proposals were put forward in the scientific community with regard to design methods and system modelling: axiomatic Design, Concurrent Engineering, and Product modelling, etc. [159] [179].

The active use of computer simulations in the design process enabled to evaluate feasible solutions at early stages. Digital prototyping permits to virtually simulate the product at different lifecycle phases while progressively moving away from physical prototyping. Thus, digital verification in design has enabled more integration with IT while guaranteeing high fidelity and accuracy of implemented models [180].

Design increasingly encompassed not only product design, but started addressing the design of products, Product-Services [181] [182] and the production environment in an integrated way. In parallel, this implied that there was no longer 'a product development cycle', 'a service development cycle' or 'a production environment development cycle'. Moreover, as all activities involved had become entangled and mutually dependent, there was no longer an overarching hierarchy in the different processes. Additionally, this meant that the development of products, services and production environments became mere aspects of an overarching set of development activities, that also needed to address focus points like the design rationale, portfolio planning/management, knowledge synthesis, etc. – that traditionally would not have been covered by the individual cycles. This underlined the need for an information-based approach, where indeed the information content was the backbone of all development activities.

Another point of complexity, implicit in the product development process, also related to managing information and knowledge [183]. Moreover, the knowledge involved in the development process activities was the subject of numerous studies, which would enable it to be capitalised on and managed. Subsequently, knowledge management also became a major focus of these new industrial practices. Many approaches have been proposed: case-based reasoning [184], graph-based-reasoning [185], enterprise modelling [186], design project memory [187], etc. Digitalisation has been a great mean capturing high skilled tasks in industry [188].

The main objective for knowledge capitalisation and management approaches was to be able to trace both business and decision-making processes as well as exploit the stakeholders' knowledge using different concepts, activity flows… Despite the differences in the scientific origins, design science on the one hand, computer science on the other, some models were able to make the connection between both knowledge management and engineering design [189] (e.g. how similar are 1/knowledge modelling : Activity diagram, hierarchical modelling, etc. and 2/meta-models for product modelling: e.g. [190] [191] [192]. Knowledge-Based Engineering was an emerging topic within the two disciplines [193] thus supporting knowledge synthesis throughout the entire PDC. Among many industrial applications, the MOKA approach was used in the aeronautic industry at the Airbus Company [194].

Consequently, it is fair to say that complexity within product development processes has continued to increase over the past 40 years. The undertakings of modelling, analysis, and choices relating to product life cycles are ever more numerous today. The literature discusses the entire cycle from requirements to dismantling activities. The interfaces (i.e. relationships) between the inputs and outputs of these activities must also be managed comprehensively in order to really master the entire life cycle's complexity (i.e. closed loop of the PLM) [195]. Knowledge management aims at capitalising on each engineering task's inputs (design intentions, choice, and decision) and outputs (definition of the product) with a clear objective of reusing (e.g. the 6W capitalisation approach [196]).

3.2.2. Complexity within industrial organisations

Industrial organisations within the manufacturing industry also faced major developments given the changes that were taking place in the global industrial ecosystem.

Small, local companies that had remained like this for many years started expanding, learning how to manage vertical and horizontal organisational interfaces as well as adapt to international technical and economic developments in order to maintain their level of competitiveness. "The company no longer represents a simple member belonging to a well-defined industry but rather forms a component of a business ecosystem that crosses a variety of industries" [9]. Subsequently, new organisations started appearing within the manufacturing industry, revealing a real business network among which today are found: 1 / the major clients in specific industrial sectors (e.g.: Airbus in the aeronautical industry, the PSA group in the automotive industry, etc.) who moved towards assembling rather than manufacturing, 2 / tier 1 subcontractors who designed and built the functional sub-assemblies of the systems, 3 / tier subcontractors greater than 2 whose expertise was in design, manufacturing, engineering, etc., 4 / consulting companies (man & expertise) whose numbers and growth increased to overcome the limits of internalising all skills within the same company.

It is easy to imagine that the development of this industrial ecosystem network only served to increase the complexity of the organisational interfaces that needed to be mastered and adapted by each entity to achieve the best performance. In addition, while the years 1970-2000 saw the industrial values (i.e. KPIs) mainly based on shortening production times and reducing production costs and the logistics chain, the beginning of the 2000s saw the emergence of new values [197] that focused on for example customers [198] and environmental impacts [199]. New criteria and KPIs were thus introduced and contributed to developing industrial practices, which in turn moved towards eco-design and industrial ecology in many organisations [200].

3.2.3. Complexity within the product

The progression in complexity also affected products. Gradual industrial developments saw systems based purely on mechanical technologies evolve, with massive development within the IT sector, and now network-connected technologies (i.e. industry 4.0). The literature is full of physical cyber systems and smart products (Fig. 6) [3].

The development of system complexity also encompassed the advances in its life cycle, societal and global environments, and the number of stakeholders that the engineering process (and the production process [201]) required. The engineering process therefore had to consider the notion of the system of systems including of course not only the product but also the 'enablers' system made up of organisational elements, production elements, human resources, etc. [202]. We can of course cite both the automotive and aeronautic domains for which international competitiveness requires massive customisation [203], innovation and agility, as well as the energy sector (nuclear power plants, wind and photovoltaic field, dams, etc.) for which the development of its major infrastructures will take place over several decades with life cycles of up to 100 years.

Again, complexity here relies on every physical, organisational, human, societal, and political interface that needs to remain agile in an ever changing industrial world.

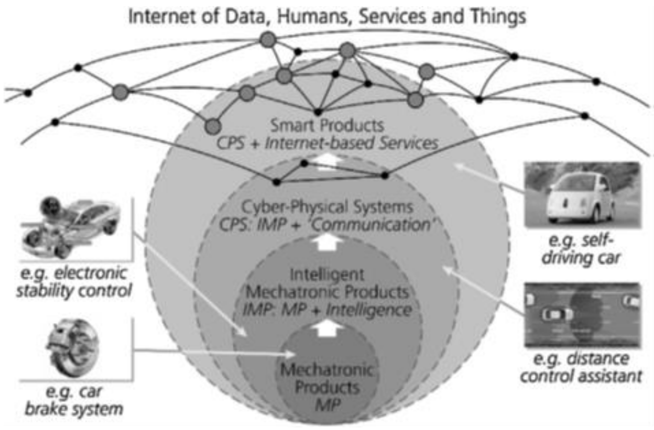

Fig. 6. Illustration of the new generation of smart Product (extracted from [3]).

3.2.4. Complexity within information technology

With the development of CAD as a support for business activities, as seen in section 1, the 1990s saw the emergence of information systems that would promote collaborative activities. The first elements of Electronic Document Management initiated in the 1950s were at that time used to support the product development process: Metadata, indexing, document storage, etc. The first PLM (Product Lifecycle Management) tools and concepts [204] were marketed in the 2000s by the main CAD vendors: TeamCenter from Siemens, WindChill from PTC, Smarteam and Enovia from Dassault System [205], [206].

Subsequently, the 2000s saw incremental advances in these PLM solutions:

- Within their functions, the simple management of CAD documents commonly called PDM (Product Data Management) was extended to encompass the management of documents / items of the entire life cycle. The term PLM was thus born.
- Within their architectures, which gradually evolved from low-level programming environments (unix console, etc.) to ergonomic user interfaces. This made it possible to democratise the uses of PLM in product development processes and to break away from the strong dependence on IT departments.

- Within their inclusion with CAD applications. Indeed some editors (e.g. Lascom Advitium…) were not from the world of CAD but still offered PLM solutions. Their market share therefore included non-manufacturing industries that did not use CAD solutions (i.e. geometric modelling) in their activities.

Openness and democratisation in the academic world is still encouraged by both historical vendors and by the emergence of certain free solutions (Aras Innovator, Odoo, BeCPG, etc.). It is of course unthinkable to compare these two types of solutions, but this makes it possible to support 'learning by doing' approaches which seem to us to be a fundamental point at the present time (see sub-section 4.3.3).

All specific features that are connected to the fundamentals of PLM solutions [207] [208] and that have a direct relationship with the PDC and organisations are as follows:

- Articles and documents that defined any element that could be dealt with in the management system. These elements are, in the majority of approaches, linked to a product nomenclature (BOM - Bill of Material). With the progressive development of PLM systems, several BOMs appeared to describe the nomenclature of the system in the different phases of its life cycle (engineering e-BOM, form features CAD-BOM, manufacturing m-BOM…).
- Managing organisations so as to deliver data to each user of the specific rights / role management system. This also make it possible to define workflows representing the document creation / modelling / validation processes.
- Configuration management which make it possible to define maturities and successive versions of articles during the collaborative development process. Some will see the similarity with the concept of Branch and Trunk, for a long time used in versioning software applications [209]. This enables us to gradually freeze solutions during decision-making while at the same time retain everyone's access rights in a collaborative approach. It also make it possible to work on different variants of a product in order to meet each of its specifications in a societal environment that currently requires a mass customisation of systems.
- The visualisation of the articles and, in particular, the digital model, which can then be inspected during a collaborative project review.

PLM functions as an advance in collaborative document management are widely deployed in other phases of the system's lifecycle as well as in other industrial sectors outside the manufacturing domain. Beyond the PLM solutions used during the development phase of the system (falling part of the V cycle of system engineering), ERP (Enterprise Resource Planning) systems play the same management role in the production, assembly, maintenance and supply chain phases of the system's life cycle (rising part of the V cycle) [210] [211]. As a PLM system, it enables the articles, documents and stakeholders that are connected to or involved in these phases of managing production to be organised.

Collaborative document management is also implemented outside the manufacturing industry. For instance, the building industry also used PLM solutions to manage the collaborative modelling of buildings, road infrastructure, etc. [212]. Here we are talking about BIM (Building Information Management) which allows each of the stakeholders (master contractors, project owners, service providers, etc.) to visualise the updated and shared digital model in 2D and 3D [213]. This second phase of industrial practices therefore made it possible to link the so-called "authoring" applications, which allows for the creation of data models on the system, to "data management" applications. The latest developments in Dassault System's 3D Experience platform are in line with this guideline, offering combining all the business, management and organisational tools required by the company in a single working environment.

Despite a significant functional interest in the collaboration and management of the product, the complexity in the development of centralised information systems resides implicitly in the complexity of the architecture, the interoperability of these architectures coupling the authoring and management applications, and in their industrial deployment, which needs to be accepted and used efficiently in and by industrial organisations (e.g. [214]). These interests and limits will be revisited later on in this paper to discuss the necessary substantial investment that could have become a break in industrial agility.

3.3. A limit in the progress of digital solutions as a support for product development activity

Despite the enormous interest we have in the major developments in information technology, organisations, and products, our first analysis shows that a gradual separation emerged between IT developments and organisational changes. The evolution in the increasing joint complexity of organisations, systems and information technologies presented in the previous sub-sections shows a rupture / disjunction between organisational needs and IT solutions, which are either no longer being developed as a support for organisations or are not really fully accepted by the organisation and thus are not used efficiently. These statements were highlighted in 1978 after CAD and CAx were first implemented[215].

3.3.1. Insufficient deployment of organisational advanced concepts and information technologies in the industrial sector

Several scientific experts expressed the fact that "very few conceptual solutions proposed in the scientific community of design sciences are actually deployed in the industrial world" [216] [156]. This analysis is also described in [217] giving some causalities and indicators.

Knowledge management is also an understood and specialised topic in many industries. Unfortunately, knowledge capitalisation is not implemented in the way it should be: 'acquire and save now to reuse tomorrow'. The vision of 'reuse' (modelling for X) is currently a short term vision but the long term vision of retrieving all the knowledge (data, decision making) from the entire PDC (6W concepts [218]) is absent, which is today still a real obstacle to agility. The following sub-section will discuss why capitalisation was not perceived at its fair value, due to the RoI having very little scope.

In addition to the deployment of advanced concepts, most industrial organisations worked hand in hand with the major software companies as vendors, which orient any deployment to be done in a relatively techno-advanced way. This approach, amplified by the increasingly high frequencies of software updates (between 1 and 2 years), forced organisations to adapt to the solutions rather than the inverse.

3.3.2. Insufficient alignment between organisational needs and the functions provided by software solutions

The previous sub-sections looked at how complexity has developed in the manufacturing industry. We also focused on the current industrial needs related to horizontal and vertical continuity that ensures high agility, which is nowadays fundamental in order to remain competitive and survive in an ever changing world.

Unfortunately PLM software solutions remain document-centred applications thus putting a brake on digital continuity that should ensure the propagation of changes and therefore the agility in the development processes of products.

Unfortunately vertical continuity based on values & KPIs is not supported in software solutions. The problem of alignment with international political issues, national and societal policies and industrial values and roadmaps is still relevant. A very good example concerns all the world congresses related to energy consumption (e.g. [219]) that are still of very few incidence so far in industries.

3.4. The key factors in separating the evolution of digital solutions from industrial organisations

Our joint analysis of the academic and industrial world has allowed us to highlight certain key factors in this rupture between the evolution of CAD-PLM-ERP digital solutions and industrial organisations. Organisational changes have undergone IT changes, which have driven tool development in a techno-centric direction rather than in virtuous coevolution.

3.4.1. The rapid development in IT

The extremely rapid development in computing over the past forty years and more particularly in data structuring, GUI capabilities, etc. has seen an increase in the interest in how it can be used in society, but especially in the manufacturing industry. Much of its activity has therefore been dedicated to integrating these solutions (hardware and software infrastructures) into organisations' daily practices.

The time invested and the daily use of these tools has gradually reduced the time spent on scientific and technological expertise for reflection and innovation on the product itself.

3.4.2. Organisations focus on management and procedures

The ever changing political, technological, and societal landscapes has meant that daily transformations need to take place in organisations, core businesses and outputs. Moreover, the current global industrial context has turned industry to a short-term vision based on financial capital values. Therefore:

- Industrial organisations have been focusing more on management and less on business expertise, know-how, etc. Frequent human turnover has thus led to a heavy loss of skills.
- The strategies based on an increasingly short RoI has meant that the focus on long term innovations has moved to focusing on optimising performance in industrial activity
- The standards/procedures, which were seen as highly efficient, have pushed common sense aside along with the instinctive reactions/decisions that come with real expertise [220].
- Industry lacks of investment in training [221] and time, necessary to continually increase and improve its expertise and capacity so as to integrate new PDC concepts and digital technologies [222].

3.4.3. An ever changing industrial world requiring continuities

In the current industrial context impacted by increasingly frequent changes, organisations need be more and more agile. This agility must be based on the ability to propagate changes and assess their impacts. On one hand, vertical organisational continuity is fundamental to aligning decision-making at different industrial levels (strategic, tactical and operational) with performance indicators, while horizontal continuity ensures the links between the knowledge and data of each stakeholder in the system's life cycle. Here we find support for the concept of Concurrent Engineering.

Unfortunately, current software solutions do not really support these vertical and horizontal continuities.

3.5. Training engineering collaboration and IT platform

During this second period of industrial practices, training relating to software solutions also evolved. However, although design methods (concurrent engineering, DFX…) began being taught in higher education institutions, industrial implementation was relatively slow. Nevertheless, there was an increase in consulting agencies that took the lead and started bridging the gap between academia and industry, thus enabling these developments to be transferred to industrial organisations.

With regard to CAD & PLM software, academics had to adapt to the constant improvements in digital solutions. Learning moved increasingly towards IT feature learning and away from product modelling support. Those former are now hand in hand with later that strongly drive the roadmap for digitization. Unfortunately, it creates a disruption between organisations and engineering whose developments are not integrated into commercial solutions. This disruption is also felt in training activities, which lead to confusion [223].

3.6. Collaborative platform benefits for the PDC

In this second phase of industrial practices, it was commonly accepted that software solutions provided real support for industrial organisations. Indeed, several industries (e.g. Dassault Aviation, Naval Group…) declared that their products would be developed 100% digitally (e.g.: Falcon…).

Unfortunately, it was extremely difficult to find an analysis that supported these apparent benefits quantitatively. Calculating the Return on Investment was indeed complex to measure, firstly because the return on investment was strongly dependent on the reuse of digital models: modifications, propagation of changes, etc., and secondly because the RoI measurement had to be carried out with long-term objectives in mind; sometimes over several decades.

3.7 Synthesis: promising and profitable digital support for collaboration but an effective misalignment between the PDC and organisations

The divide between the evolution of industrial organisations, faced with the contextual complexity and the systems to be developed, along with the development of related software solutions that were becoming more numerous and therefore heterogeneous, began.

The alignment between core functions relating to product development activity was only partially resolved. For example, multi-expertise integration ensuring digital continuity had to be based on syntactic and semantic interoperability mechanisms, which are still not efficient today. Knowledge management is only supported today by few tools (e.g. Kadviser, TEEXMA, etc.) but this is mainly because it is not especially part of industrial culture.

Conversely, software developments offered more advanced functions that enriched solutions but also made them increasingly more complex to appropriate. This was all the more true in SMEs, which were not the prescribers of software vendors. So who led who: vendors or the manufacturing industry? Maier & Student [224] summarised this predicament well by stating: "SMEs know that something has to be done, but they don't know how and where to start".

The graph in Fig. 7 shows the state of the proposed indicators at the end of this second phase of industrial practices:

- *Product Design Cycle*: product complexity and LC coverage indicators were now at their maximum. Design approaches provided advanced concepts to model this complexity.
- *Digitalisation*: the global IT environment composed of authoring and management digital solutions covered the entire spectrum, and its TRL reached level 9. Authoring applications and intrinsic physical properties became progressively more associated with real multi-physical phenomena. Nevertheless, some physical behaviours were still not fully understood by academics. Management applications for integration, capitalisation and change management remained limited.
- *Organisation* evolved to integrate all PDC stakeholders of the extended enterprise in a more collaborative way.
- *Coevolution* was unquestionably the indicator that moved backwards compared to the first practices. As second practices were digitally driven, the ad equation with regard to organisation needs decreased. Organisation and its related culture were becoming less and less capable of integrating digitalisation efficiently.

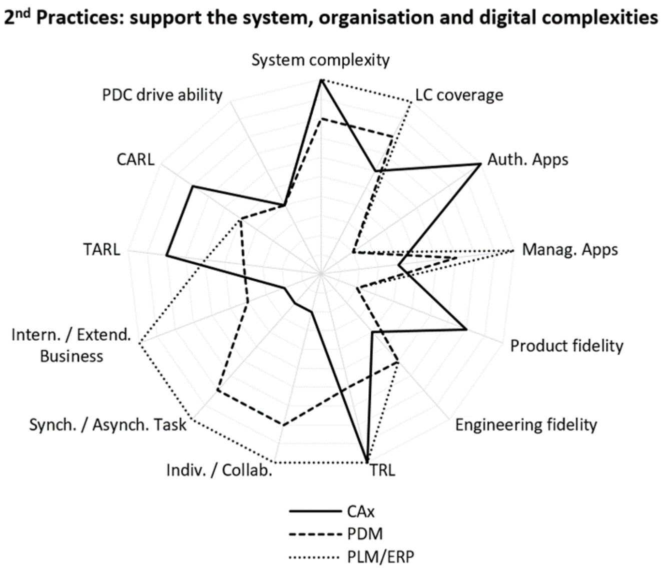

Fig. 7. Radar graph of 2nd industrial practices indicators.

4. Opportunities of new practices based on digital 4.0 transformation: a vision or reality

The divergence described in the previous section now meant that scientific and industrial communities needed to become reactive. The risk was indeed to continue in this way which would have meant that the Product Development Cycle (PDC) would have become increasingly standardised and automated, dismissing how organisation and human could act as major industrial factors for the future. Industrial effort was committed to understanding and deploying the ever new versions of the software solutions, without envisaging more efficient, agile and innovative organisations.

Collaborations and practices need to evolve in order to find a real cultural way for organisational practices and associated software tools to mutually evolve. Digitalisation has to develop alongside organisation. As expressed by [225], the "Organisational culture has been suggested as a factor that may ultimately influence the effectiveness with which a firm implements digital technologies". Organisation also has to be flexible so as to benefit greatly from digitalisation.

In this section, the authors will thus discuss the opportunities that the 4th industrial (r)evolution can provide for human, organisational and digital solutions (i.e. digital 4.0 transformation) as well as for the PDC. As presented in Fig. 2, should the reader wish to refer to the timeline, this period started around 2015 and is expected to continue into Industry 4.0. Some references already explain how technologies 4.0 (e.g. Virtual & augmented reality, Cyber physical systems, Additive Manufacturing, Big Data Analytics, FRMS, Artificial Intelligence, IoT, Simulation) are applied within the manufacturing industry [226]. We will discuss these opportunities so as to reply to the constraints expressed in the previous section.

4.1. Back to basics

As seen in the previous sections, CAD and PLM evolved from the simple development of 'tools' acting as a support for the first fundamental tasks of product development (e.g.: modelling, simulation…). They progressively became part of a heterogeneous software environment enabling certain modelling tasks and collaborative functions to be supported within an organisation in which several actors influenced each other's decisions. This development should have enhanced software tools to provide better access to functionalities relating to the PDC. Unfortunately this alignment is only part of the current reality as these software tools are based on predefined organisations and processes that do not allow for the necessary freedom of agility needed in current manufacturing industries [227]. Indeed, Industry 4.0 approaches need to adapt to changes that have become daily, and whose predefinitions should no longer exist. Thus, PDC stakeholders are being provided with software tools that are no longer suitable.

In order to meet this need for realignment between industrial organisations and software tools, the manufacturing industry needs to return to the PDC fundamentals expressed in sections 1 and 2 (the PDC features):

- The life cycle concept should include every stakeholder in all decisions related to the PDC.
- The complex system and the system of systems should include the product and the 'enablers' systems.
- Multi-actors, different perspectives, multitude of information need to enrich product modelling and support syntactic and semantic continuity.
- Changes propagation and agility should be a priority as required by smart products and smart organisations so as to remain continually competitive.

Describing the current industrial context enables us to express the expected fundamental engineering functions that need to be understood as the specifications for developing digital solutions and organisations. The alignment (coevolution) between engineering requirements and digitalisation should, on one hand, be a trigger (opportunities) to change engineering practices (i.e. techno-pushed evolution), while on the other, the evolution of engineering practices should also stipulate new specifications of software solutions developments (i.e. organisation-pushed evolution). From another perspective, [11] talks about 'machine-assistive labour' vs 'labour-assisted machine'. [228] presents the technological and organisational barriers and the mutual evolution strategy to really make eco-design efficient.

Fig. 8 illustrates the PDC's fundamental functions in the current manufacturing industry:

- Model / analyse / represent information relating to systems. The PDC requirements need to take into account the stakeholders' perspectives and related knowledge for these form the initial basis on which the development of the CAD / CAx tools, discussed during the 1st industrial practices analysis, occur.
- Exchange / share documents and data. This mode of collaboration between actors is required in order to ensure

that they are always working on the same version of the project and system, which is the foundation of document management and PLM tools, as seen in section 2.

- Integrate / link all data and information together in order to propagate any changes that occur during the PDC. Vertical and horizontal continuity is thus required and must take into account interoperability issues as the industrial context is largely heterogeneous with regard to both data [229] and organisational [230] aspects.
- Manage / control / master any changes in order to be as agile as possible in a constantly evolving industrial context.

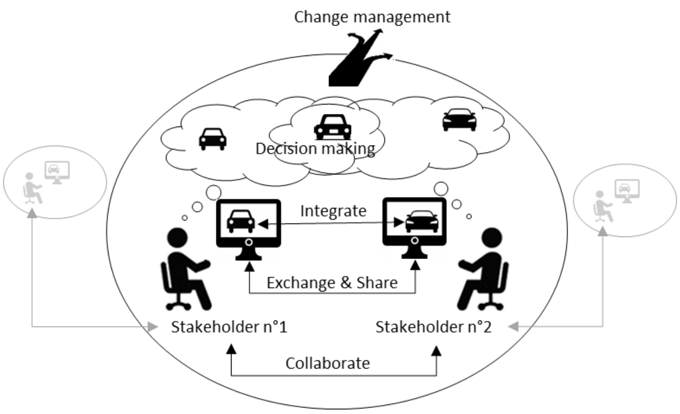

Fig. 8. Illustration of fundamental requirements for the PDC.

Functions relating to human communication and social media will not be focused on in this paper, as this is indeed another scientific field related to CSCW (Computer Supported Collaborative Work) that goes far beyond the topic of the Product Development Process.

4.2. Opportunities of Industry 4.0: industrial adoption of the incremental development in digital solutions

Many scientific and industrial articles today are focusing on the emerging technologies of Industry 4.0 [231]. A Science Direct bibliometric study based on "Industry 4.0" key words shows that the number of papers on this subject have grown from 1 in 1983 to 1 743 in 2020.

However, even though many of these technologies are not really new (e.g. virtual and augmented reality – VR & AR) they are now seen as new opportunities to support the PDC activities. In order to illustrate this new impetus for these technologies, some may speak of a second peak on the Gartner curve [232]. The first is considered a peak in technological interest: peak of inflated expectations ("I am interested in the technological features and/or performances"). The second could be considered a peak in the interest in exploitation: plateau of productivity ("I am interested in using the technology in my daily activities"). Gartner itself mentions the 'plateau of productivity' as 'High growth of adoption' that highlights authors' focus of acculturation approach.

Fig. 9 shows how VR and AR were predicted by Gartner. After being introduced in 2013, these technologies took a relatively long time to reach the 'plateau of productivity' (4 to 5 years). VR was removed from the 2018 prediction although it was still on the Slope of Enlightenment in 2017. That meant it should have reached an expected maturity. Analysis needed to be carried out on technological developmental issues. The new development in AR glasses highlighted how new technological advances initiated VR&AR adoption. Nevertheless, the adoption and the massive exploitation of VR is not really effective in industry nowadays (sub-section 4.2.1) as coevolution between organisation and the PDC never materialised.

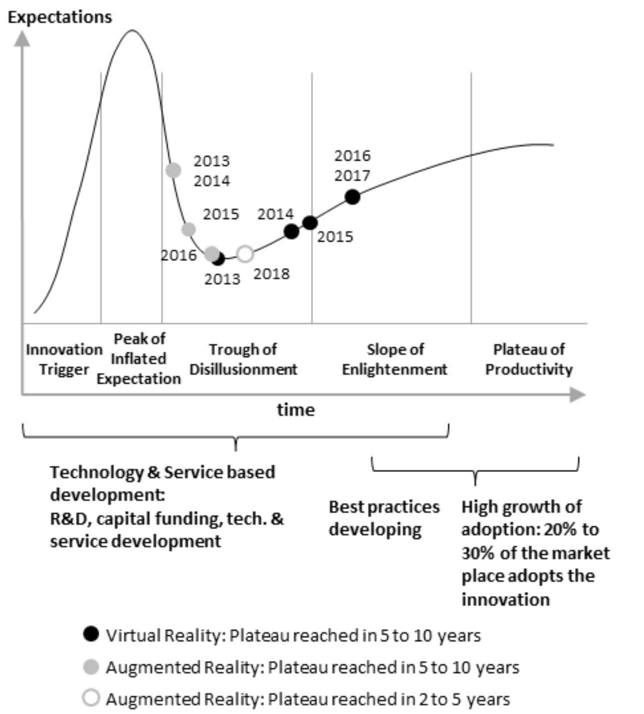

Fig. 9. Adapted from the evolution of the Gartner curves over time that shows a certain resurgence in existing technologies. Example of VR & AR.

Several other technologies, presented as Industry 4.0 technologies, although not 100% new either, have gradually evolved and been coupled thus attracting new technological interest. One can cite the concept of IoT and digital twin, which may seem new, but in fact are based on incremental evolution of digital mock ups, instrumentation technology (i.e. sensors), Hardware and Software in the loop (HIL / SIL), communication protocols….[233].

Finally, certain technologies (or approaches) are now becoming of major interest in the manufacturing industry thanks to the major developments in AI (Artificial Intelligence). The concepts of this technology (one of the first articles regarding AI date back to 1950 [234]), set in motion the development of industrial expert systems in the 1990s. They were used in Knowledge Management approaches, and found a resurgence through the expansion of statistical techniques coupled with the computing capacity of current computers.

It is therefore very important to position these so-called new technologies (i.e. 4.0 technology) in order to comprehend their insights, limits and opportunities. It is thus these opportunities that the paper will now present as a 'mirror' of the underlying industrial organisation and the PDC's main functions, and the analysis will assess how these opportunities can provide interest in order to exploit these technologies. Subsequently, it was decided that four of the most common 4.0 words that appeared in most of the analysed articles [227] [235] (VR and AR, IoT, data analytics and digital twin), would be the focus of study. Nevertheless, it must be remembered that analysing the coevolution of organisation and digitalisation can easily be transposed to any other kind of emerging technologies and concepts.

4.2.1. Virtual and augmented reality

From the first experiences in 1962 (sensorama), virtual reality evolved to see the first headset appear in 1968 (Epée de Damocles) up to the current technologies of today (e.g. HTC Vive, Oculus Rift…). As shown on Gartner's curves, it is easy to identify the first technological peak and the current second peak. The emergence of augmented reality as an offshoot of VR coupled to real world tracking and mapping is certainly a strong lever in this new interest in the PDC.

Stakeholders connected with the assembly, manufacturing or maintenance of systems indeed find it of major interest, which in turn raises the subject of development in industrial practices driven (i.e. pushed / influenced) by technology [236].

Current Virtual and Augmented Reality capabilities have thus provided new types of support for representing data:

- A new immersive representation, which should make it possible to increase the representation's cognitive capacity. For example, superimposing digital information on the virtual world will facilitate the understanding or realisation of tasks (e.g. assembly processes and operations).
- New modes of individual and collaborative interactions with digital models and particularly the digital mock-up when a physical object is not prototyped or present in one's location (e.g. remote immersive collaboration).

Therefore, it will be extremely efficient as long as it does not disrupt the stakeholders' activity. Should this be the case, the technology will more than likely be pushed aside with comments such as: "It was not bad but…". This technology is still in the process of being adopted by the manufacturing industry with regard to digital [237], [238] and social [239] facets, which has subsequently enabled us, the authors, to open up discussion on the interest in the coevolution of PDC activities, organisation and technologies.

4.2.2. The Internet of Things – IoT and digital visual management

As stated in [240], the Internet of Things is "the pervasive presence around us of a variety of things or objects – such as Radio-Frequency IDentification (RFID) tags, sensors, actuators, mobile phones, etc. – which, through unique addressing schemes, are able to interact with each other and cooperate with their neighbours to reach common goals". The Internet of Things aims to connect any object relating to a system, situation, use, etc. These objects can be physical (sensors, actuators) as well as digital data structured / modelled within the information systems. Extending the concepts of the Internet (exchanged data network) to the world of industry will allow many to respond to the horizontal and vertical continuity functions as identified above:

- The capacity to acquire information on "real" systems (People / Systems) and share it on the network
- The capacity to process system data throughout the entire lifecycle; the development phase by receiving feedback from the systems in operation, but also the operation and maintenance phases will be highly beneficial by taking advantage of analysing the physical data (e.g. real-time control, predictive maintenance, etc.).

This digital continuity would also make it possible to digitise and increase the visual management for decision making functions. Commonly called Obeya (i.e. war room), visual management was first used on manufacturing production lines. Currently, visual management is also being extended to engineering project management and knowledge creation [241]. Concerning the PDC, digitalisation and organisation, and virtual visual management (definition of e-obeya) enable the KPIs in industrial processes to be tracked:

- Be as accurate as possible with regard to real-time data (real time monitoring vs reporting of indicators)
- Share indicators with teams in the horizontal value chain / aggregate data to different indicators.
- Help decision-making at the different levels of the organisation's vertical hierarchy (value chain).

E-Obeya [242] also ensures that digital management and visualisation are more efficient. For example:

- There is a real-time display of data unlike a manual update which can lead to erroneous decision-making [243].
- Share indicators are in the right place with the right person, unlike physical displays, which are not visible to everyone at all times.
- Advanced analyses are performed by aggregating data to help better decision-making.

Consequently, from this example from technologies 4.0, it can be said that coevolution that has been well designed makes for organisations that are more efficient and open to the opportunities that arise from new approaches (e.g. data-driven decision making). However, it is still important to remember that implementing such technology requires significant human and material investment. In 1960 [244] carried out an interesting survey on both the interests and the limits of this technology.

4.2.3. Data analytics & Big Data

While Design of Experiments has been used for many years [245] to help understand phenomenological correlations [246], the growth in computing capacities coupled with the use of learning techniques (e.g. Neural networks), which have also existed since 1968 [247], have given rise to the contemporary approaches of Statistical Data Analysis. Although Statistical Data Analysis has been studied for many years [248], the approach, under the umbrella of machine learning, has appeared in technological trends since 2015 and are still in the 'peak of expectation' [249].

Subsequently, the engineering scientific community in particular has taken advantage of the many opportunities that have emerged and that can be applied to product/process modelling and analysis so as to hasten decision making activities:

- Statistical data analysis based on machine learning increases the automated capacity of interpolation and extrapolation from massive data sets (e.g. analysis of the influence of manufacturing process parameters [250] [251], data retrieval for reverse engineering [252], identification of causalities using neuro-evolution mechanisms [253] …).
- These learning approaches are also used to analyse decision-making processes. The input data thus become processes, like a series of activities, from which learning generates process patterns as well as decision rules within these patterns. This helps to support decision- making [247].

The main benefits of 'machine learning' approaches come from the increasing computing capacities that engender analysis of high-order correlations that were not possible before. However, several articles dispute these facts and argue that these new approaches do not really bring physics into the equation, but rather allow us to find 'black box' correlations that had previously not been identified with engineering knowledge. Indeed, the techniques mainly use large learning databases to correlate input and output parameters.

Statistical approaches of data analysis are an excellent example for the current limitations of the organisational and software disjunction, as mentioned above, to be addressed. Beyond this intense interest in data analytics, it is however necessary to point out that these approaches require fairly large collections of data in order to implement learning. These collections quite often limit such approaches because industrial environments are not fully ready to incorporate them [254]. The hybrid paradigm [255] proposes a combined approach using both statistics and knowledge to generate the correlations.

Thus, the opportunity is not fully exploited and a real approach to mutual organisational and modelling development needs to be reflected on beyond the unique computing growing capacities.

4.2.4. Cyberphysical systems & Digital Twin

The focus for the last key technologies 4.0 will turn to the concept of digital twin. The scientific community has shown a major shift in interest towards technology due to its state-of-the-art capabilities [256]. This interest is also found on the Gartner curves, which integrated the digital twin in 2018 and has extended the twin concepts to the society concerns since then.

Like the technologies presented earlier in the section, the analysis shows that the digital twin is not a technological leap in itself but more an evolution and a pooling of several other technological building blocks. These approaches, commonly known as cyber-physical systems [257], aim to combine the systems' digital and physical behaviours so as to mutually improve and enrich both systems [258]. [259] presents a model in which 8 characteristics could be used to have a foot-print of a digital twin. Both physical and digital behaviours must be mutually linked (i.e. twinned) so as to obtain more accurate, global physical/digital behaviour in real time, which will be updated when changes occur in either the physical or digital parts of the system. A digital twin is more than a digital mock-up; more than a digital simulation; more than a monitor for sensors. A digital twin embeds all the technologies and benefits of IoT, digital mock-ups, digital modelling, and statistical data analysis to provide a new way that will be a real support for digital continuity [260] in order to manage real-time changes in the systems, and therefore in decision-making. The advances in physical data must impact the results of digital analyses, which will then make it possible to make the right decisions during the entire product lifecycle (e.g. design & production [261], maintenance [262], etc.). In CAD, the 3D form features are no longer the leading model, but rather, and most importantly, a pivotal one combining product design, production environment design, and all the other life cycle phases that are becoming essential. This has to do with IoT and sensing, but first and foremost with connectivity that gives quick feedback loops in the global product lifecycle [263]. E.g. plant simulation may influence design features in an integrated and real time manner.

4.3. Training for the coevolution of the PDC features and technologies: a new culture for academics and industries

The previous section highlighted how new technological trends offer new industrial opportunities. It is nevertheless important to remember that unless these technologies implement the solutions that meet the fundamental requirements presented in Fig. 8, they will not be beneficial. It is therefore important to recall that many organisations currently lack this global PDC vision, only replacing old technologies with new ones without perceiving the progressive construction of the information system, organisation, and the industrial process, which are seen as one, thus respecting the essential fundamental PDC building blocks.

This section deals with the major point addressed in this paper: how to ensure coevolution of product development practices & human organisations and digital technologies.

As stated in the above sections related to 'training', it was seen that the first period was opportune for the expectations of the PDC and the functions provided by the CAD-CAx technologies to be aligned. However, the second period saw a separation appear that was clearly reinforced by training practices that focused on tools as software functionalities rather than a support for the PDC activity's functionalities. It is therefore essential to rethink how training should be carried out in order to find an alignment between the two.

4.3.1. The need of acculturation to integrate new technological developments

The successive advances throughout the three periods of practices were analysed in sections 2, 3 and 4 respectively. Nevertheless the current relevant difficulty arises when having to adopt to concepts, understand concepts and technology features (i.e. digitalisation), and understand efficiency. In 1994 [264] compared the US and Japanese cultures in order to potentially adopt technological innovations. [222] reported that 62% of the brakes for digital transformation came from an absence of industrial/technological/training culture. Fig. 9 adapted from Gartner's curves also shows that the 'plateau of productivity' is reached once 20% to 30% of the market place adopts the innovation: "Don't invest in a technology because it's hyped, don't miss it because it's out" [232]. The other phases of the time line are indeed techno-centred.

A potential benefits of mutual development of technologies and organisations would then be the merger of the two Gartner's peaks. The importance of such mutual organisation and digitalisation (i.e. 'hardware' technology) 'acculturation' was also introduced to face ever-increasing industrial competition [265].

4.3.2. Coevolution of Product Development Cycle, organisation and digitalisation: which is in the lead? Which owns the system?

We have just seen that technologies 4.0 bring real opportunities to the PDC. That being said, it is fundamental that these new approaches are not viewed only as 'hypes' but rather as a support for organisational product development activities. Therefore alignment must be respected in order to achieve efficient coevolution.

CAD has become a tool that is used to work on a model rather than integrated into a model. And it is from here that the problem of version/configuration management and 'where are my files' starts, and which is still ongoing. Not only do product developers need to move from custodians to orchestrators, but users need to become separate entities as well, for they are not the CAD system's 'engine', but rather the 'drivers' [23]. [266] traced the history of CAD development and deployment in American academic circles and industries during the 1980s, explaining clearly through the 'dominant image' (Fig. 10) that current technology development is "rescuing humanity" (e.g. automation…) instead of "humans and machines living alongside one another". Of course, the availability of technology does not alone transform into good practices. It is an enabler, but not necessarily the main driving force. As [267] states, "He has developed an argument in support of cultural unity between technology and society, as illustrated by the bi-directional links between a computer and its user".

The two questions - which is in the lead? Which owns the system? – have naturally emerged to drive future scientific investigation that should strongly combine engineering and human sciences.

This sub-section certainly opens the door to several questions albeit without really providing answers but which should raise questions for the reader, academics and manufacturing industries, on their future training approaches:

- How do academics and industries learn about the developments in engineering methods?
- Do industrial needs drive developments generated by academia and vendors?
- Do vendors drive industry providing new capabilities beyond the updates? Are these capabilities 'accepted' by the manufacturing industry?
- Where do the PDC & organisation strategic / future ideas for paradigm shifts come from? Currently they are seen as emergency measure approaches.
- How can we co-construct this paradigm shift?

The answers to these questions should be used as a real opportunity for academic and industrial organisations to define a 'good' roadmap, a set of principles that support this new paradigm's joint acculturation where both the PDC and new digital technological features are jointly developed for better global efficiency. The next sub-section will present some training-based solutions. Section 5 will present a scenario that should take this discussion further looking at how this new paradigm may be implemented in the future.

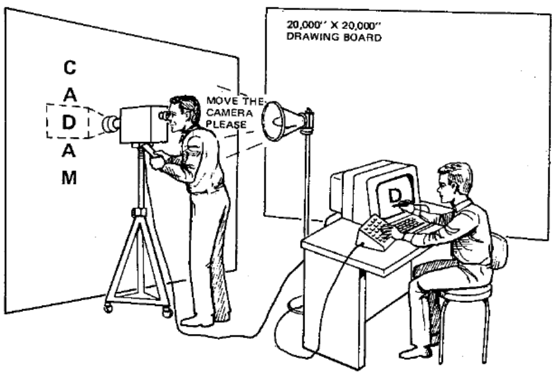

Fig. 10. Illustration of the mutual understanding between human organisation and digitalisation (extract from [266]).

4.3.3. Are 'gamification' and 'learning by doing' approaches potential solutions for teaching/learning the coevolution of the PDC, organisations and digitalisation?

As already presented, one of the limitations in the joint evolution of digital technologies and organisations is the different levels of acculturation. These levels are in fact due to a lack of joint ownership mechanisms, which nowadays remain mostly techno-push. Learning practices are surely a good way to shift to a new coevolution paradigm. Therefore, by continuing to analyse learning development, as presented previously in the paper, it is necessary that all players reflect on the pedagogical practices so as to anticipate future technological, industrial and societal advances. "Teaching was no longer the production of uniformity but the guidance of diversity. The first step in good teaching became finding out and understanding each student's sense of direction" [266]. Learning organisations should therefore develop their programmes in order to become increasingly agile in the face of these changes and at the same time remain as close as possible to both CAD technologies [268]–[271] and the 4.0 industrial world [272]. This agility is nowadays also required by learners, either during initial training or lifelong training:

- Each learner has different initial skills, whereas the level of students in engineering education was fairly homogeneous 15 years ago.
- Each learner has different training objectives with regard to the future development of his or her career. One will want to move towards scientific and technical expertise, the other towards management functions while another will want to become an entrepreneur.
- Every learner wishes to advance as quickly as possible during training. Indeed, today's students have more and more desire to take their own training programme in hand. One would like to take a break for personal reasons, another would like to combine different subjects that are not 'normally' combined (e.g. engineering & history, engineering and human science…).

'Learning by doing' approaches have always been interesting teaching methods used to enrich and supplement theoretical learning outcomes (i.e. knowledge) with practical learning outcomes (i.e. know-how). Innovative 'learning by doing' [273] or 'project-based learning' [274] approaches give meaning to training courses as those who are enrolled on these courses learn what will be relevant in the situations they will encounter. Thus, this underlines what is applicable and real in the workplace rather than teaching certain theories of knowledge that may no longer/not be appropriate in the engineering domain.

With regard to product development approaches, as explained in sections 2, 3 and 4, training has turned to using digital technologies, subsequently moving away from the main approaches, methods and models related to the PDC. Paradoxically the latter should be taught first so as to respect the expected functions of engineering activities (Fig. 8). Moreover, this move is appearing in many training situations due to a 'conceptual/philosophical' vision of the PDC fundaments. The current generation of engineers and learners are more comfortable when 'tools' are used to support the training activities.

With this in mind, the concept of a 'learning factory' has often been used over the past few years [275], [276], [277] to provide 'tools' and 'real life situations' to teach theoretical concepts of 'lean manufacturing' in a more comprehensive way. These educational practices and platforms have made it possible to create suitable practical scenarios (i.e. serious games) allowing for joint acculturation of theories and technological elements and advances (e.g. [278]).

Would it be possible to deploy and experiment with these approaches as part of the PDC-related practices? Some examples of gamifications, already used in industry [279], are providing very good results [280], and should be progressively developed and used in academic studies.

For this purpose the authors propose a three-phase training approach to increase the ART and CARL levels presented in table 1, which would avoid a unique techno-pushed way of acculturation and support co-training among concepts, organisations and technologies instead:

- Phase 1 (technoless acculturation): this first phase will provide knowledge of the technological and methodological concepts irrespective of any handling of the technological tools, thus giving the learner a real understanding of: 1/ the costs and gains that a method or technology can bring, 2/ the prerequisites of know-how and technologies for current or future developments. This phase will be carried out without using "real" technological tools so as not to couple and confuse the constraints/gains related to the technological deployment with the gains/costs of the technology itself. The two do not have the same implementation and horizon effect.
- Phase 2 (learning by doing): this second phase will make it possible to touch on the technological elements while remaining within a "learning by doing" framework. In other words, the learner will need to be able to use and adapt the technological components to specify/propose a solution in line with his/her needs (do the things right). They will then be fully immersed in the joint development of practices and technologies; each feeding the other in a virtuous loop. Open source solutions as Arduino, FreeCAD, etc. are very good examples. They indeed provide customisable elementary blocks.
- Phase 3(business implementation): this last phase is similar to what manufacturing industry does when deploying/integrating new technologies. The aim is to gradually introduce new engineering practices and technologies into their industrial processes. This phase is generally implemented using POC (Proof of Concepts) and Use Cases so as to be 100% operationally deployed.

It is noted that the failures in coevolution training, assessed by ART and CARL levels, are mainly due to the learners' ignorance of the overall balance between limitations, costs, and the potential gains of the concepts and technologies that are taught. Therefore it increases the difficulty and speed of integrating them into the manufacturing industry. [266] clearly depicts that CAD/CAM development and integration should not have a unique purpose of competitiveness, investment and finance.

4.4. Technologies 4.0 benefits for the PDC: promising and profitable digital support that requires quantitative assessment

Assessing the extent to which digital technologies have, or have not, made the Product Development Cycle (PDC) more efficient is an important factor. These evaluations should be based on the performance indicators related to the fundamental PDC functions, presented in Fig. 8: Model, Share, Collaborate, Exchange, Integrate, and Manage, raising the questions:

- Is modelling enriched and better exploited? The digital twin approaches have supported this positively by implying that capitalising on data structures and engineering processes is fully efficient [281].
- Do IT platforms improve collaboration? Although there are numerous and efficient collaboration tools, there are still gaps that depend on the desired functions within organisations. [282], who studied 94 articles on collaboration, illustrates how the human factor is somewhat overlooked in respect of collaboration tools within for instance the BIM field.
- Is interoperability a solved issue? In the current situation, industry relies on vendors to accommodate scaling and integration issues; it is assumed that vendors take responsibility for providing the interoperability. In a world that is dictated by new information types, and new scales of information replenishing and speed, 'neutral' formats may have lost their credibility along with the expectations that were previously promised. Nowadays, 'neutral' formats seem to address one aspect of interoperability rather than proffer an overall solution. This results in an incredibly complex network of interdependencies that stresses the need to revert to the understanding of why applications are connected. From here, the denotation of interoperability becomes more essential than just a process-oriented exchange. Thus, some mechanisms are currently proposed either for digital data [283] [284] or for cyber physical data in heterogeneous cyber physical systems [285].

Despite a number of publications on the subject of assessing PDC performances [286], it is still difficult to truly confirm that digital technologies have improved PDC efficiency for the studies were carried out qualitatively on highly heterogeneous objects (types of companies, size, complexity of the product, etc.). [287] carried out a study that produced the first insights into CE benchmarking approaches to design products. Subsequently, quantitative assessments in design sciences have emerged as a core factor in this paper. As with other disciplines (computer vision [288], biology [289], pharmacological research [290], etc.), it seems important to be able to provide the scientific community with laboratory experimentation frameworks (test bed [291], database - https://www.dmu-net.org/, performance indicators…) in order to assess the impact of scientific and technological advances. This new outlook is now being introduced at the CIRP STC-Dn community and can thus start building on the existing founding elements [292].

Fig. 11 shows the characteristic assessments of the PDC, organisations and digitalisation following the third phase of industrial practices related to opportunities originating from technologies 4.0:

- *Product Design Cycle*: remains in the same position that was reached at the end of the *2nd practices* phase.
- *Digitalisation*: digital technologies continue to generate an increasing number of opportunities to support the PDC fundamentals related to multi-physic analysis (data analytics) and visualisation (AR/VR). Fidelity integrity also increases with the IoT and digital twin concepts. However, knowledge capitalisation and synthesis functions are still lacking when compared to the progress made in academia.
- *Organisation:* this is still extended and collaborative despite the development of business models that are moving towards externalising non-core activities.
- *Coevolution:* this is certainly a weak indicator as organisations are still techno-pushed. Acculturation opportunities (common sense, learning, benchmarks) are nevertheless being proposed so as to improve organisational and digital development alignment.

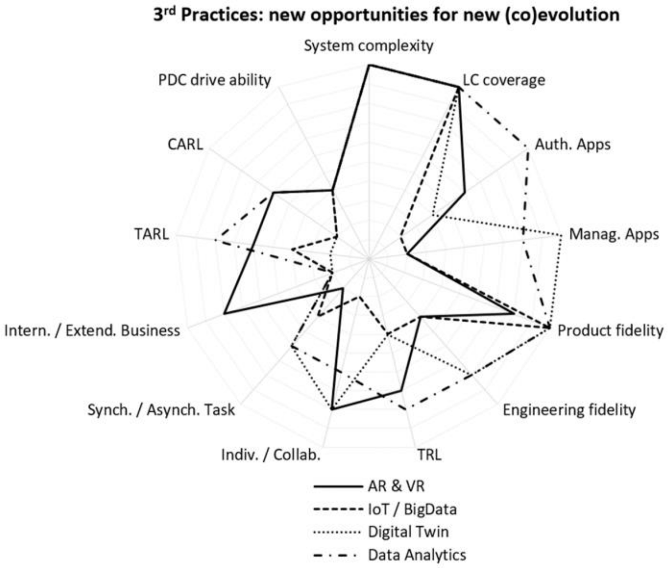

Fig. 11. Radar graph of 3rd industrial practices indicators.

5. Future practices: Synthesis and Prospective

By way of conclusion, this section will firstly present an overall view of the development in the methodological approaches related to the Product Development Cycle (PDC), industrial organisations and related digitalisation. Secondly, it will look at the prospective scenarios of mutual advances in current and future industrial and societal contexts. These possibilities should open discussions for future reflection and the PDC guidelines for academics and manufacturing industries.

5.1. Overview of the coevolution of the Product Development Cycle and digitalisation

Sections 2, 3 and 4 presented the advances in product development, related industrial organisations including Human and ongoing software developments (i.e. digitalisation) envisaged to support these activities.

The characteristics and their respective levels, presented in the introduction, represent the scales of development. Fig. 5, Fig. 7 and Fig. 11 show how each of the elements (new concepts, new IT solutions) enable these characteristics to be implemented during the three phases in industrial practices.

Fig. 12 shows the macro level of each of these phases of practices. The assessment of Fig. 1 indicators is currently qualitative. A number of recent studies could be reviewed so as to provide more accurate initial indicators and to quantitatively provide technological forecasting that would take both digitalisation and organisation and human into account [293]. Nevertheless, major changes in product development approaches, including changes in industrial organisations, coupled with major digital developments have led to the following synthesis:

- On one hand, it can be observed that product complexity, organisation development, and LC coverage have reached a good level of consideration and digital support (North East and South West dials of the radar graph on Fig. 12).
- On the other, organisational development is still mainly driven by technological advances as acculturating theoretical concepts and design approaches is more often than not perceived as efficient (cf. sub-sections 3.3 & 3.4) (North West and South East dials of the radar graph on Fig. 12).

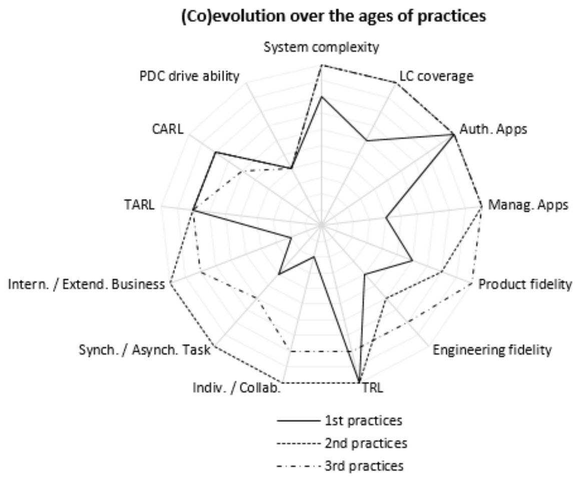

Fig. 12. Overview of the PDC and digitalisation coevolution over the past, current and future industrial practices.

Thus for future reference, intentions and progress must be included in these acculturation mechanisms (North West dial) so as to return to common sense measures with regard to the PDC and improve engineering's fundamental fidelity (South East dial).

5.2. Guidelines for coevolution within the manufacturing industry's ecosystem

The intellectual reflection that has taken into account industrial development and its implicit complexity, the interesting advances of digital solutions that have brought major benefits (e.g. automation, speed, capitalisation), and the break in conceptual and IT joint thinking, presented in section 3, must surely be the major concerns that should be at the core of the manufacturing industry's current ecosystem. Section 4 introduced the opportunities brought about by the concepts of Industry 4.0 to support the continuity/alignment in the PDC and digitalisation development. However, the lack of common culture and practices for mutual implementation still remains a real obstacle.

It is fundamental to find patterns of acculturation and common reflection between all ecosystem stakeholders; the manufacturing industries, solution providers, and academics so that scientific and technological advances are understood, appropriated and industrialised with the greatest efficiency. The characteristics presented, although they may change in the future, should serve as a 'guide' for reflection.

5.3. Prospective: what could occur in the manufacturing industry and society's future

The previous section summarised the parallel developments of engineering approaches (i.e. PDC approaches) and the associated digital software (i.e. information technologies). This synthesis has generated a number of recommendations that focus mainly on a required mutual way of thinking and how technological and industrial organisations are going to develop. The following sub-sections will thus focus on the authors' reflections with regard to potential scenarios. Each scenario will focus on a specific evolution tendency:

1. The PDC, manufactured and IT systems will continue to focus on increasingly complex development albeit in different ways. Digitalisation will be regulated by natural trade-offs (unable to follow the speed of progress) but due to a lack of acculturation, humans will be unable to use it efficiently.
2. Data will take the lead position, ahead of Human in driving the decision-making processes in which Human will become a resource.
3. People, Society and planet Earth will regulate/control the PDC, industrial activities, digitalisation and decision making. A new paradigm will emerge.

These three scenarios should be springboards that will enable current thinking to encompass an ecosystem that goes beyond the manufacturing industry and its stakeholders (customers, supply chain, etc.), to include society at large. This will give us an insight into seeing how new values (planetary impact, people, know-how, etc.) can become the drivers of the future industrial systems, new technological developments, and vice-versa [294].

Based on the development analysis presented in previous sections, the scenarios and the authors' reflections present what could be future trends. Nevertheless, as they only present prospective tendencies, this generates more questions than statements.

5.3.1. Financial capital is still leading industry of the future, regulated by endogenous levers

In 2030 industry will continue to absorb the advances in digital and production technologies that will continue to provide better quality and precision for the products. These advances will be used in the current logic of going ever faster and always cheaper to meet the continual relentless fierce international competition.

The integration of technological advances is still based on a techno-push approach, and the acculturation gap continues to widen. Humans execute tasks mainly driven by technology's new functions and possibilities, and industrial organisations and decisions continue to rely on financial capital. Behaviours and values remain unchanged and the system continues to be regulated by international geopolitical decisions, international movements based on resource prices, laws, regulations… Global industry and technological innovations are becoming increasingly uncertain because they are strongly influenced by external (exogenous) factors such as the major nations' development policies, geopolitical influences, capital groupings, etc. The global economy is becoming increasingly complex and the impact of these factors is becoming more and more substantial [295].

There is really no new external trigger to influence the situation. Digital continues to penetrate industrial practices (cloud based modelling and computing, IoT, Big Data, digital twin, etc.) and financial capital remains the medium in exchanges and discussions. Companies have entered an era of 'agility to survive'. Large innovation projects are led by large private investors (Hyperloop, etc.) but do not sufficiently penetrate the entire value chain so as to impact the manufacturing industry and particularly SMEs.

However, the implementation of new solutions in 2030 will be impacted by the industrial system's endogenous regulations: technologies and humans will be limited by their productivity and working capacity respectively. Looking at this from a less pessimistic perspective, regulations are being established so as to combine financial capital, hitherto primordial, and other capitals that will make it possible to envisage new internal levers for technological and industrial development. The lead-time, which has been continuously reduced in order to bring it back to a financial value, has been moderated. Faster is seemingly no longer considered the best. For example: the supply chain and human capacities are reaching their maximum and will thus be unable to go faster. Lead-time is becoming an unsustainable value (i.e. key capital), and is now being balanced against social capital (e.g., finding a personal/professional balance) and know-how capital, which enables a certain scientific and technological mastery to be established in order to make the best decisions with regard to solutions.

5.3.2. Data takes the lead position

From 2020 to 2030, digital growth will continue to increase to the point where data analytics will control all socio-economic decisions. The world will be managed by computers that analyse human and industrial behaviours, and so in this context, humans will merely implement/follow orders. The development and choice of innovations will be calculated from the trends assessed by artificial intelligence algorithms. "On the Replacement of Humans with Machines: A Different Humanism", Downey speculates on a hypothetical future shape of society in which the dominant cultural image of technology would not assume "that technology stood outside of a society" [266].

The development of approaches/beliefs on data analysis coupled with the increase in digital technologies in the industrial and social world is today causing very radical changes in the way of thinking about the next industrial era. Nowadays, this 'data-based' tendency is already showing considerable influences:

- For the past 25 years, the massive democratisation of the internet and e-mails in society and the industrial world has greatly impacted on human behaviour [296]. It is obvious that this has enabled societies to connect to the world and has provided an increasingly rapid means of communication. This increase in speed, the 'time reduction/minimisation' has implicitly influenced social and industrial expectations, which today make it an important indicator of values. We must always react more quickly (e-mails have accelerated exchanges and reduced expectations uncertainty through no longer having to wait for an answer), we must pass orders more quickly (suppliers establish quotes based on delivery time/end users accept quotes based on delivery time).
- Human behaviour has been impacted by the emergence of 'virtual' social networks. These new personal and professional networks obviously have real connection benefits but also real drawbacks as many relationships have become impersonal and furtive. How many employers and academics assess people's values based on which professional social network they use (e.g. LinkedIn, research gate …) and how they use them.
- Industry is now looking to gaining knowledge and making decisions based heavily on statistical learning. Although it is accepted that data analytics is of great interest in finding parameters and phenomenon correlations (cf. sub-section 4.2.3), it is also accepted that the results are still only a support and not based on a real understanding of the correlations. This situation naturally calls into question the years of generating and cultivating expertise so as to find the balance between phenomenological know-how and the understanding of physical and natural phenomena.

The radical solution of this scenario could quite easily lead to a data takeover in the social and industrial world. The data, which could then define its own decision making values, would affect Human with regard to low added value tasks. A real drawback of this data-based 'surveillance' on the economy is presented in [297]. Since Human is fundamentally imperfect and uncertain, it may no longer have any value for data, which will therefore take the lead.

Today, however, statistical learning are still based on learning mechanisms for which humans play an important role in creating data for 'validator' (e.g. supervised or reinforced learning techniques). A more moderate vision of this scenario would subsequently be to find the right balance of a dual Human Intelligence and Artificial Intelligence.

5.3.3. Society, Human and planet Earth are exogenous regulators

Since the era of Industry 4.0, human generations have become aware of the environmental urgency that threatens its habitat: the Earth. In 2020, several studies have shown that energy over-consumption linked to industry as well as to social practices (displacement, digitalisation, personal over-consumption, etc.) has had an irreversible impact on the planet's resources [298]. The studies carried out by [299] also show that the environmental impact is not only influencing the geological land (climatic warming, melting ice, etc.) but also the living species. The new generations are naturally concerned by this impact, which will most probably have major consequences on the economic values that have governed the world for several decades.

In 2030, 'good' social practices will subsequently become the world's regulator. They will create a balance between the specifications, development, industrialisation and the use of new technologies, while carefully monitoring their frugal needs and their environmental impact. These new values will be fully accepted by all the stakeholders throughout the entire value chain. Vertical decision-making will be fully aligned with politics, industries and society and new debates will be imparted into the social and industrial systems. The guidelines will call for a review of consumption patterns that will no longer consider energy needs as always achievable because they are themselves at the root of the global environmental and societal changes. Solutions must therefore be based on a value principle aimed at reducing overall energy consumption [300].

Yet, the wealth of global technological know-how must not be forgotten as it has improved the world in many areas, such as access to energy, water, etc. So, let us cite a few paradoxical examples: the Internet: although it has introduced virtual communication between people, thus reducing physical travel, it has also increased energy consumption through the production of equipment, data storage and transmission, etc.; the emergence of electric mobility, which has reduced the use of fossil fuels and greenhouse gas emissions but which has affected natural resources (rare earth metals) and increased the demand for electric energy.

The radical solution to this scenario would be to leave the current industrial technological world and align the world with the new values that would emerge, but this is just utopian in thought. Consequently, it seems more reasonable to find a balance between technological developments and the minimum vital needs in a collective global minimisation and sharing of resources. Frugality coupled with new technological advances may therefore be the right balance for future thinking, and societal and industrial systems. This mutual top-down/bottom-up influence of technologies on Society is illustrated in [294]. It presents how new-age technologies are playing a role in providing an innovative offering for the social good. In the same topic, [301] puts forward a study that highlights how technological, organisational, and environmental factors influence SMEs' decisions to implement digital technologies in smart manufacturing activities.

6. What could be some new paradigms for a future roadmap in engineering design science

To resume these proposed scenarios, it seems essential to give a significant place to the trade-offs present in each of the situations. It also seems important that mankind should be able to maintain its role as a regulator in the face of global impacts and the impact of digitalisation and data analysis in its decisions. Indeed, the authors remain convinced of Human's deep intelligence to find the correct balance when faced by the new uses of AI and by the impacts on the planet Earth.

New paradigms are thus proposed by the authors to propel the future roadmap in engineering science and to better merge the future development of industrial organisations and digitalisation as a support for PDC.

6.1. Agility and frugality for engineering resilience in an ever-changing world

As discussed in [267], the COVID-19 pandemic has made people aware of how necessary it is to be adaptable and thus react rapidly to a situation. "How aligned are the corporate and IT risk registers". "One of the greatest risks in risk management is missing a risk". Beyond the extreme health situation that we find ourselves in today, society must really wake up to the fact that these kinds of realities are becoming progressively more frequent. Subsequently, organisation and IT systems need to be well aligned and developed in order to provide this agility. "An IT strategy fully aligned with organisational objectives would have been better equipped to deal with COVID- 19 than a less mature strategy" [267]. [286] presents agility as one of the levers of competitive positioning. Moreover [302] explains that individual and corporate culture "yields competitive advantages in an innovative, fast changing environment". This confirms that 'acculturation' may be a good driver for the PDC, organisation and digitalisation coevolution.

For instance, the organisations whose employees are used to working remotely have been more rapid in reacting to the new working conditions implemented due to the Covid-19 lockdown. In addition, IT agility and associated functions (e.g. cloud data storage, etc.) have also improved the resilience and capabilities of the global organisational and corporate systems. Business resilience can be defined as the ability of a business to anticipate, prepare for, and respond and adapt to incremental change and sudden disruption in order to survive and prosper [303].

In addition to that resilience need for industry, it is important to think of the principles of frugality, which will also steer future developments in engineering design for manufacturing industries [304] [305]. Frugality should indeed be one of the major change in Human behaviours in the next decade. What meaning does each one give to an environment that needs to be as sustainable as possible for our industries, society, people and the planet? Frugality in the products we design, manufacture, deliver and consume. Frugality in organisational activities and human 'enablers'. In this we perceive, of course, the fundamental concepts of Lean, which are sometimes forgotten, and to a greater extent not implemented. Frugality in the development of enabling technologies and digitisation, which is currently part of our industrial and personal daily life.

The paradigm of engineering for agility, frugality and resilience is thus one of the scientific roadmap that should be enriched. Even if the reflection already exists, the horizons of short-term industrial RoI are no longer the answer to the long-term horizons of societal changes.

6.2. Enaction-based decision-making to judiciously combine Human and Artificial Intelligence

As introduced in sub-section 3.4.2, one of the factors in organisation and IT's incapacity to adapt was the fact of having progressively removed Human from their development loop. In the majority of decision-making processes (design, production, etc.) Human was certainly the most flexible system. Indeed, it is still to this day, faster at changing its 'programming' and decision-making and progressing in these tasks depending on the development of the necessary work to carry out (innovation, reconfiguration of production systems, etc.). It is faster than reprogramming a robot. It is faster than new machine learning. Conversely, its capacities and 'production' qualities will be much lower in the medium and long term than AI or a robot programmed specifically for a certain task. These they will be able to carry out at great speed and precision (undoubtedly more so than Human).

It is therefore interesting to take advantage of current advanced technologies, but it is essential that humans and know-how retain the role of moderator, which was one of the recommendations proposed in sub-section 5.3.3. This precondition is also considerably visible within industrial organisations that have been, and are increasingly driven by processes and procedures that govern activities and decision-making. Humans have therefore entered a 'management' mode that encloses them in predefined schemes that are often no longer appropriate given that the context has evolved and is no longer the same as that in which the schemes were defined. Risk management and planning for events that happen very seldom create overheads that could be often considered unproductive [267].

As [220] states, it is important to give meaning to action and 'instinctive' decisions, which in turn gives rise to an awareness and agility. Thus the term 'enaction' signifies that the following of objective patterns will be replaced by following the knowledge and skills acquired from each person's activity and personal interpretation. Here the opposite is perceived: 'do the things right and not the right things' [300]. The 'least commitment approach' [306] is thus a good way to lead PDC. These are presented as the good paradigm to follow in order to refocus the product development processes on human expertise and know-how and less on a prescriptive process and data-based modelling.

6.3. Quantitative indicators and scientific validation framework to bring together academic advances and industrial developments

This paper has underlined the importance for the PDC, organisation and digitalisation to evolve mutually so as to obtain true alignment (i.e. same outcome objective). [307] confirms that these three factors will be the new drivers for new product development. Subsequently, the last paradigm shift that we would like to end with will focus on the common acculturation and Return on Investment indicators. Indeed, the separation seen in section 3 and the opportunities presented in section 4 will only be effective if stakeholders are able to assess the common interests and advantages in developing organisations and technologies, otherwise each will continue to advance towards its own interests and the already identified gap will continue to widen.

If one wants to assess the impact of digitalisation on the PDC, and organisation and vice-versa, the first concern will be to identify and characterise the PDC performance indicators and the technology acculturation maturity levels in organisations.

With regard to the PDC performances, some references have already presented indicators [286]. However, Industry 4.0's RoI impact can be different when comparing SMEs and MNEs. While SMEs are struggling with decision-making on integrating technologies 4.0 [227], MNEs are suffering from many issues that are stopping them from fully implementing advanced technologies: investing in technical resources, organisational culture. Decisions "are mainly based on the manager's/decision-maker's 'gut feeling'" [235].

Concerning maturity models, indicators show how technologies, including digital 4.0 technologies, are implemented [235] and become successful [308]. However, [309] argues that technologies are so far not meeting industrial expectations. Fig. 13 demonstrates what happens when industry 4.0 technologies are applied to the manufacturing system maturity.

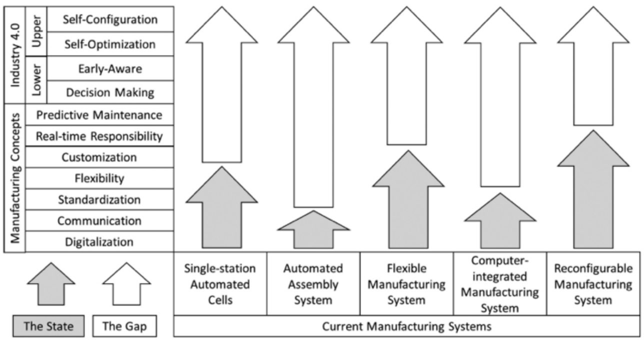

Fig. 13. Illustration of the gap between current industry 4.0, maturity and expectations (extract from [309]).

[310] provides 9 factors with which to assess industry 4.0 maturity. As shown in Fig. 14, one can retrieve certain elements that may be adapted to the three pillars highlighted in the paper: the PDC (operations), Organisation & Human (Governance, People, Culture) and digitalisation (Technology). Future work could study these dimensions from an engineering design perspective. Obviously, it is also important to be able to qualify / quantify these levels of maturity and RoI. As already specified, TARL and CARL indicators and relating acculturation processes should be one aspect that future academics will study. [311] presents the results that can assess how ready SMEs are to integrate IT.

In sub-section 4.4, the authors also introduced this quantitative concerns with a scientific perspective. It therefore seems judicious that the academic world can take up the subjects of experimentation frameworks for validation in the Science of Engineering and Production quickly. As did other scientific domains, it must be fundamental so as to assess the medium and long-term impact (e.g. knowledge, understanding, performances) of current scientific developments on the society and industrial eco-system.

7. Conclusion

Through a practices timeline, the paper presents the evolution of engineering activities and three pillars of it: Product Development Cycle, digital technologies and industrial organisations.

Radar graphs represents the maturity of these evolutions at the end of each of the four practices and highlight that some characteristics of the three pillars can be further improved.

By focusing on the keynote of this paper, the authors can conclude that it is now fundamental that each stakeholder understands the importance of the coevolution between: 1 / the product development processes, which are becoming increasingly complex, 2 / the development of technologies, which make it possible to go ever faster, to be ever more accurate to understand, model and capitalise products and decision making, and 3 / the development of human organisations, which no longer seem to know how to slow down / manage the speed of daily industrial changes and their impact on their competitiveness.

The paper thus depicts some prospective scenarios and scientific roadmap to draw some new trends in engineering design development.

Dimension	Exemplary maturity item
Strategy	Implementation I40 roadmap, Available resources for realization, Adaption of business models, …
Leadership	Willingness of leaders, Management competences and methods, Existence of central coordination for I40, …
Customers	Utilization of customer data, Digitalization of sales/services, Costumer's Digital media competence, …
Products	Individualization of products, Digitalization of products, Product integration into other systems, …
Operations	Decentralization of processes, Modelling and simulation, Interdisciplinary, interdepartmental collaboration, …
Culture	Knowledge sharing, Open-innovation and cross company collaboration, Value of ICT in company, …
People	ICT competences of employees, openness of employees to new technology, autonomy of employees, …
Governance	Labour regulations for I40, Suitability of technological standards, Protection of intellectual property, …
Technology	Existence of modern ICT, Utilization of mobile devices, Utilization of machine-to-machine communication, …

I40…Industry 4.0, ICT…Information and Comm. Technology

Fig. 14. The 9 dimensions of industry 4.0 maturity [310].

8. Glossary

BIM – Building Information Modelling/Management
CAD – Computer Aided Design
CAE – Computer Aided Engineering
CAx – Computer Aided X
ERP – Enterprise Resource Planning
FRMS – Flexible and Reconfigurable Manufacturing Systems
HIL & SIL – Hardware and Software in the loop
IA – Artificial Intelligence
IoT – Internet of Things
KBE – Knowledge Based Engineering
KPI – Key Performance Indicators
KM – Knowledge Management
MBSE – Model Based System Engineering
MES – Manufacturing Executing System
PDC – Product Development Cycle
PLM – Product Life Cycle Management
RoI – Return on Investment
TRL – Technological Readiness Level
VR & AR – Virtual & Augmented Reality

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