

Smart design engineering: leveraging product design and development to exploit the benefits from the 4th industrial revolution

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Abstract

The 4th industrial revolution (IR) requires new products and business models adjusted to the rapidly changing market conditions, which calls for evolutions in design engineering. In this context, smart design engineering is here defined as a methodology used during the analysis and design of a product or a system, which can be composed by hardware, software and/or services, and that explicitly considers exploiting the technologies and opportunities from the 4th IR. This work contributes to both design theory and practice: (i) it deepens the understanding about the necessary smart design engineering features and shows how these features impact the product design and development process's (PDDP) key dimensions (procedures, people and tools); (ii) it maps the features' impact on PDDP's phases, thus providing practical direction for process improvement. To accomplish these results, a survey was performed on the initial features presented in the literature, which helped to identify new features and to confirm their relation to the 4th IR and their impact on the PDDP. These features were then analyzed against the 4th IR environment perspectives and core technologies, which led to understanding how they can be used to improve the PDDP.

Key words: smart design engineering, 4th industrial revolution, Industry 4.0, smart industries, product design and development

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1. Introduction

Although the industrial revolutions (IR) impact first on the shop-floor, they affect all the processes through the companies' value chains. To illustrate these changes Pessoa & Jauregui-Becker (2020) consider seven business and market perspectives, where: (i) the technology increase of the production performance; (ii) the production performance leads to cost reduction and/or allow the developing of new products; (iii) the newer/more affordable products better fit the market needs and increase sales; (iv) the production and the product's environmental impact raise society awareness; finally (v) a compatible product design and development process (PDDP) is required to deliver products capable of exploiting the previously mentioned benefits. [Figure 1](#) summarizes the perspectives evolution; the ellipses highlight some bridging elements from the 3rd to the 4th IR.

Consequently, taking full benefit from the changes pulled by the 4th IR requires new products and business models adjusted to the rapidly changing market

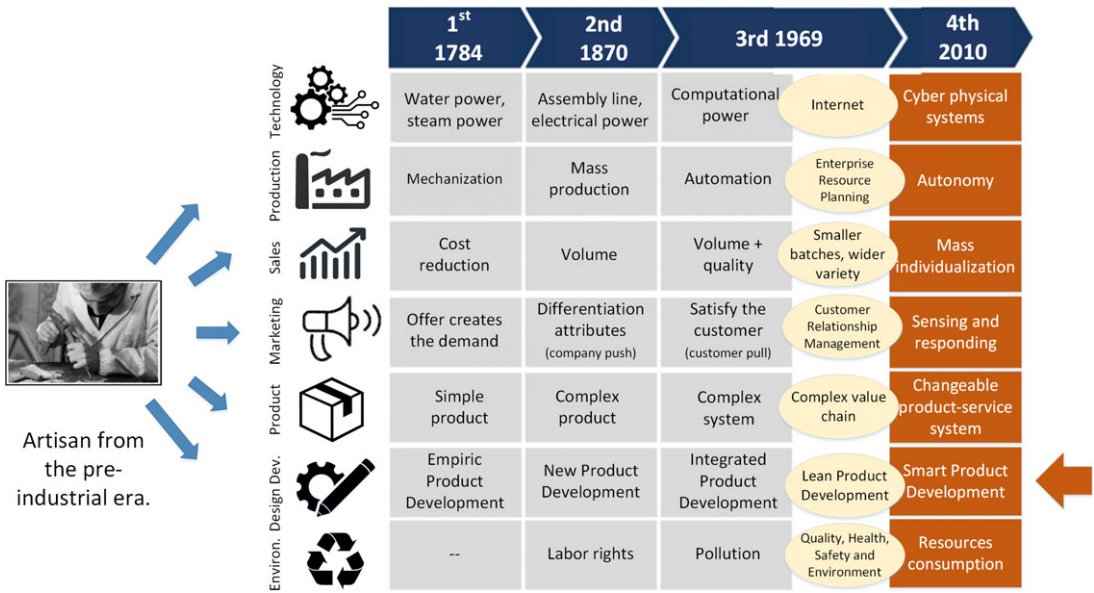


Figure 1. Changes driven by the industrial revolutions – adapted from (Pessoa & Jauregui-Becker 2020).

conditions (Reeves *et al.* 2016). In fact, even though smart factories can better support the manufacturing of individualized products and avoid the sub-optimum use of their resources (Verzijl *et al.* 2014; Wang *et al.* 2015), and smart products have the potential of better serving the needs of its customers through information exchange and adaptiveness (Wolfgang Maass 2007; Porter & Heppelmann 2014), these benefits are only achieved if the products are designed accordingly (Rüßmann *et al.* 2015).

Smart design engineering is here defined as a methodology used during the analysis and design of a product or a system, which can be composed by hardware, software and/or services (therefore not limited to designing smart products), and that explicitly considers exploiting the technologies and opportunities from the 4th IR. Therefore, Smart design engineering leads to process improvement by including 4th IR features, while design of smart products leads to incorporating 4th IR technologies into the products themselves. This work aims at contributing to both design theory and practice by: (i) deepening the understanding about the necessary smart design engineering features; (ii) mapping the features’ impact on PDDP’s phases, thus practitioners can benefit from the presented results to improve their PDDP process.

In this work the term “Industry 4.0” was used rather than Industrie 4.0, which is the original German for the 4th IR. While Industry 4.0 focuses on the communication among cyber-physical systems (CPS) and its impact on the shop floor, the 4th IR expands the core concepts from Industry 4.0 by including changes outside of the shop floor (i.e., products, customer attitude, business models, etc.).

1.1. Smart design engineering: the road so far and the strategy for going beyond

Previous work on analyzing design principles for Industry 4.0 either fail on discussing specific issues related to 4th IR impact on the PDDP. Hermann,

Pentek & Otto (2016) performed a literature review on principles that affect the design of Industry 4.0 scenarios but did not address the PDP itself. Similarly, Wang *et al.* (2016) compare the Industry 4.0 production system and traditional production line without discussing possible issues related to product development. Lu (2017) conducts a comprehensive review on the topic but presents no findings about its impact on the engineering design process. Pessoa & Jauregui-Becker (2020) performed a literature review and identified 10 initial findings, which would shape smart design engineering (Table 1). The initial findings require further investigation about its completeness. Additionally, no clear reflection on their practical impact through the product life cycle is presented, which is an obstacle to their implementation into the PDDP.

This paper aims at filling this gap by and further describes the 4th IR impact on design engineering and through the PDDP. In order to achieve this objective, this work starts from the smart design engineering features first identified by Pessoa & Jauregui-Becker (2020) and conducts a four-step research, each step aiming at answering a specific research question. Figure 2 shows how the paper was structured for following these steps and achieving the main objective.

- Step 1. Are there more smart design engineering features than the initial 10 findings? To answer this question, specialists and researchers were asked if they would add any other feature to the initial findings. The respondents were the same 11 specialists contacted by Pessoa & Jauregui-Becker (2020) and 14 attendees from the smart design engineering and PSS workshop at the CIRP IPSS 2019 Conference. The choice of the CIRP IPSS Conference was due to its alignment to the product evolution perspective, as presented in Figure 1.
- Step 2. Do all the features indeed relate to the 4th IR? As part of the previously mentioned questionnaire, the interviewees classified the features against its relation to the 4th IR and its impact on the PDDP. The respondents received a blank chart as in Figure 4 and were asked to plot the features according to their best knowledge.
- Step 3. Which 4th IR-related new technologies, new trends or new needs are relevant to each feature? A cross-relation analysis is made among the features, the industry perspectives (Figure 1) and the nine 4th IR core technologies (Rüßmann *et al.* 2015).
- Step 4. How these features impact the PDDP phases' activities? The impact on the process, people and tools elements is analyzed and plotted into each PDDP phase.

2. Resulting features considering the survey results

Considering the topic's novelty and the scarcity of specific literature, a survey was performed to gather the opinion from specialists and researchers. The objective here was to further validate the completeness and relevance from the 10 initial features that served as the base for this work.

2.1. Features' completeness

The survey participants were asked to identify additional features to the initial set, which resulted in the preliminary features listed on Table 1. There were no two

Table 1. Preliminary features list.

#	Feature	Remark
1	Design for empowered users	Initial 10 features set from (Pessoa & Jauregui-Becker 2020).
2	Design for product in use feedback	
3	Design for changeability	
4	Design for data analytics	
5	Design for cyber security	
6	Design for emotional interaction	
7	Continuous engineering supported by MBSE	
8	System lifecycle management	
9	Increased stakeholder quantity and complexity	
10	Changes in quality perception	
11	Workers as knowledge finders and processing experts	Features added by the survey respondents.
12	Open and low-cost innovation	
13	Human-centred design of systems	
14	Recognizing the value of data, models and information	
15	A part and the part's history data cannot be dissociated	
16	Design for the flexible adoption of new technologies	
17	Support for innovation and disruptive product lines	

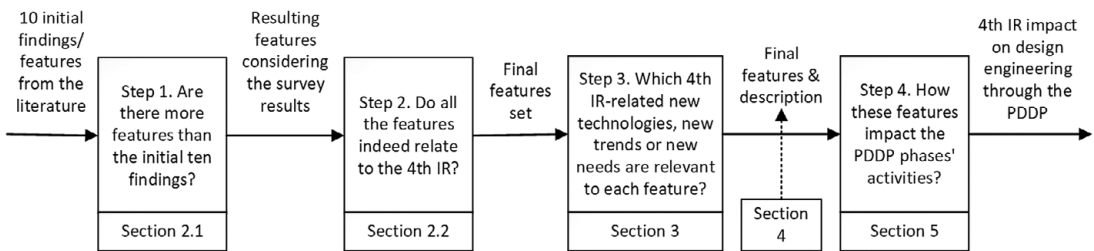


Figure 2. The paper's structure and the research steps.

respondents proposing the same additional feature and some of the propositions could be traced back to the initial set (Section 2.2). Here is the preliminary features list including both the original set as proposed by Pessoa & Jauregui-Becker (2020) and the ones coming from the survey:

1. **Design for empowered users/customers:** Customers can be empowered to become active parties in product creation activities, both at the design process's front and rear-ends.
2. **Design for product in use feedback:** Products can be outfitted with sensors that enables knowing the product's actual performance and condition, which

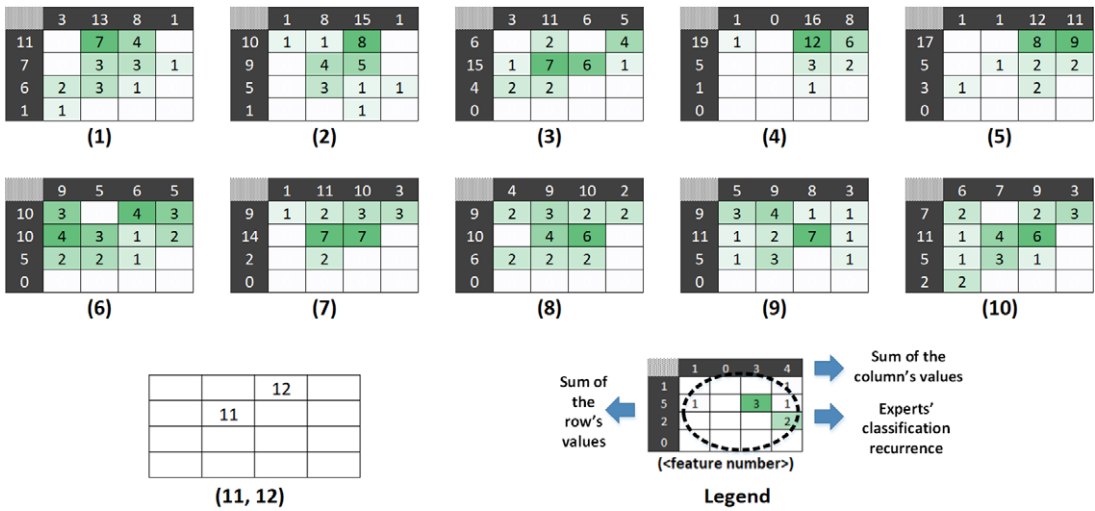


Figure 3. How the experts rated each feature.

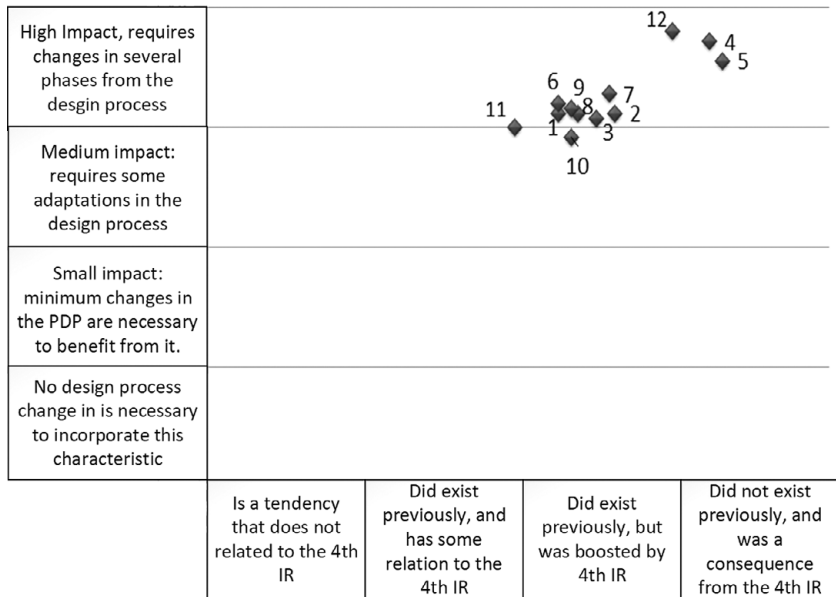


Figure 4. Features' final positioning.

might give insight for updating or upgrading the product and helps determining a better and tailored maintenance strategy.

3. **Design for changeability:** Products are changeable by having built-in robustness against small use variations, adaptability to different use experiences and new technologies, and flexibility to updating and upgrading. Set-Based Concurrent Engineering is an example of approach where solution alternatives coexist through flexible modular design (Ward *et al.* 1995).

4. **Design for data analytics:** Design engineering can benefit from the sheer amount of available product data, external data, and enterprise data, where big data analysis can be then performed through the various activities during the product design, manufacturing, and service.
5. **Design for cyber security:** The communication among the systems and the use of internet bring the challenges and threats from the cyber world to the physical world, which means security must be embedded as a first principle in product design and across the value chain.
6. **Design for (emotional) interaction:** By adding communication capabilities, the new products might interface and collaborate with other smart products and with the people in the environment. The product should be designed not only to providing functionality, but to creating the right emotional response and emotional bounds between user and product, while avoiding the possible failure modes that might arise from these interactions.
7. **Continuous engineering supported by model-based systems engineering (MBSE):** Continuous engineering builds on simultaneously considering all engineering disciplines and on the foundation of systems engineering practices by persistently applying engineering tools, methods, and techniques to address change and close gaps between design models and requirements. In this scenario, model-based systems engineering (MBSE) supports new product design processes that integrate design methods.
8. **System lifecycle management:** The product lifecycle-related information availability, quantity and change rate requires models and tools that effectively support decision making. Product Lifecycle Management (PLM) solutions should be dynamically adaptable reflecting the ongoing changes of data models (including hardware, software and services perspectives) and capable of determining the cross-impact of changes among these perspectives.
9. **Increased stakeholder quantity and complexity:** Modelling smart products requires taking into account the complete product lifecycle and an interdisciplinary and transdisciplinary collaboration with several intermediary stakeholders, such as the ones that can give insight on market, technology, legal, sociological, psychological (emotional interaction) and environmental.
10. **Changes in quality perception:** Quality perception is becoming rather dependent of personalized goals and experiences than on generally accepted aspects by the target market, where design, safety, quick availability, and personalized service quality are gaining higher importance. Another aspect to be considered is the concern about privacy and data security.
11. **Workers as knowledge finders and processing experts:** Considering the fast pace of knowledge creation, is very unlikely that someone masters the whole set, even if it is related to a specific topic. Designers must develop a skillset that includes good understanding on how to find, select, combine, and use the knowledge available.
12. **Open and low-cost innovation:** Design processes should take advantage from the knowledgeable and creative individuals outside the company, which can also contribute to achieving strategic goals, reducing innovation costs, and which sharing intellectual property both ways is useful.
13. **Human centred design of systems:** Solutions to problems should be developed by involving the human perspective in all steps of the problem-solving process and thus addressing the core needs and well-being of those who experience the problem.

14. **Recognizing the value of data, models, and information:** Data, its aggregation into information, and its modelling to facilitate the retrieval and processing become central.
15. **A component and its history data cannot be dissociated:** A component (physical product) will always be accompanied by data about its origin and history. This feature implies the need of defining and guaranteeing the keeping track of each component's history information through its life cycle.
16. **Design for the flexible adoption of new technologies:** The exploding availability of new technologies requires PDDP and product platforms capable of incorporating them in a fast and cost-effective way.
17. **Support for innovation and disruptive product lines:** New product development is often seen as an improvement of their actual products and/or actual way of doing business. The exploding development of new technologies is always a threat to the establishment, so companies should foster (disruptive) innovation to be ahead of the competition.

2.2. From the preliminary to the final features set used during the analysis

By analysing the 10 (initial) + 7 (survey result) features, the set was reduced to 12 features by considering the following rationale:

1. Feature 13 (human centred design of systems) is a technique that supports better addressing the stakeholder needs and therefore was merged to feature 10.
2. Feature 14 (recognizing the value of data, models, and information) is already included in features 4 and 7. The former deals with data and information choices and data modelling, while the latter deals with information modelling.
3. Feature 15 (a component and its history data cannot be dissociated) implies the need of defining and guaranteeing the keeping track of each component's history information through its life cycle, therefore it was merged to feature 8.
4. Feature 16 (design for the flexible adoption of new technologies) was merged to feature 3.
5. Feature 17 (Support for innovation and disruptive product lines) is related to set-based concurrent engineering (SBCE) and can be considered part of feature 3.

2.3. Features' relevance

The respondents also determined the features' relevance according to their link to the 4th IR and to the extent their implementation require changes in the PDDP. [Figure 3](#) shows the results the accumulated results, where each feature from 1 to 10 is presented individually. Since they were cited only once by specific respondents, features 11 and 12 are presented in separate. The lines' and columns' meaning are shown in [Figure 4](#); the x -axis links the feature to the 4th IR, and the impact on the design process is represented in the y -axis.

The features final positions ([Figure 4](#)) were determined by calculating the mean of the histograms (row's and columns' sums) from [Figure 3](#). All features are closely related to the 4th IR and have relevant impact into the PDDP. Features 4 and 5 were rated as the most characteristic from the 4th IR.

3. Features analysis against 4th IR trends and technologies

The cross impact among the perspective affected by the IR as presented in Figure 1 shows that no single perspective can be analyzed individually. In this sense, the identified features can both influence (↑) and be influenced by (←) the general context's trends (Table 2):

1. Cyber physical systems are not only transforming the shop-floor; its use in the most diverse applications is a supporting/triggering factor to many features that need exchanging data through secure communication channels (Lee & Lee 2015; Monostori *et al.* 2016; Dawid *et al.* 2017).
2. Autonomous production means that the machines can collaborate and solve production problems without human intervention (Porter & Heppelmann 2014; Park *et al.* 2017). The integration through the supply chain and the resulting better data accuracy and traceability is a powerful support to that (Eigner *et al.* 2014; Gerhard 2017).
3. Mass individualization becomes possible if the customer is placed at the centre of the design process (Luchs, Swan & Creusen 2016), so the designed building blocks support the expected configuration possibilities. Also, in use feedback support the product's adaptation to the user using profile (Rodríguez-Mazahua *et al.* 2016; Dawid *et al.* 2017). In this way, mass individualization can fulfil the diverse customers quality expectations.
4. Marketing trend of sensing and responding requires that diverse stakeholders are taking into consideration and that the products give in use feedback (Broy, Cengarle & Geisberger 2012; Luchs, Swan & Creusen 2016); in this way the right

Table 2. Features and 4th IR trends.

	Cyber-physical systems	Autonomous production	Mass individual	Sensing and responding	Changeable PSS	Continuous product	Resources consumption
F1			↑		←	←	
F2	←		↑	↑		↑	
F3			↑	←	↑	↑	↑
F4	←			↑		↑	
F5	←	↑	↑	↑	↑	↑	
F6	←		↑	←		↑	
F7					↑	↑	
F8	←	↑	↑		↑	↑	
F9				↑		↑	←
F10			←	←	←	↑	←
F11						↑	
F12						↑	

↑ Feature influences perspective trend
 ← Feature is influenced by the trend
 <blank> no relevant influence

Table 3. Features and 4th IR core technologies.

	T1	T2	T3	T4	T5	T6	T7	T8	T9
F1						←	←	←	
F2	←			←	←	←	←		
F3	←	←		←	←	←	←		←
F4		←	←	←	←	←			←
F5			↑	↑	↑	↑			
F6	←				←	←			←
F7		↑	↑						↑
F8			↑		←	←	↑		
F9					←				
F10	←	←			←	←	←	↑	←
F11			←			←		←	←
F12					←	←			

↑ Feature supports technology
 ← Feature is supported by the technology
 <blank> no relevant relation

emotional interaction can be developed towards users with diverse expectations (Dawid *et al.* 2017).

5. Changeable products and product service systems (PSS), and which can deliver the expected quality, should be designed accordingly (Mehrsai *et al.* 2014). While their flexibility can support higher configurability, they can benefit from models and systems that integrate the data and make easier the reusing and the dealing with variants in the case of changes (Xue *et al.* 2012).
6. Product development should be supported by a whole set of new design principles to support a quicker response to the market’s need, through continuous product development (MacDougall 2014; Porter & Heppelmann 2014). At some extent, all the identified features have impact in the PDDP and contribute to continuous product development. Each specific feature is further described in Section 4.
7. There is a consensus on the direction of reducing the consumption of resources; changeable products and PSS brings the possibility of updating and upgrading only parts or modules, instead of changing the whole product and having unnecessary wasting (van Rhijn & Bosch 2017).

Besides the 4th IR trends, the features were also checked against the 4th IR nine core technologies according to the Boston Consulting Group (Rüßmann *et al.* 2015). Table 3 presents which features can both influence (↑) and be influenced by (←) the technologies:

- T1. **Autonomy:** autonomous, flexible and cooperative systems.
- T2. **Simulation:** leverage real-time data to mirror the physical world in a virtual model.
- T3. **Horizontal and vertical system integration:** companies, departments, functions and capabilities use universal data-integration networks to enable truly automated value chains.

- T4. **Internet of Things (IoT):** field devices and even unfinished products can use IoT to communicate and interact both with one another and with centralized controllers as necessary. It also decentralizes analytics and decision making, enabling real-time responses.
- T5. **Cybersecurity:** the need to protect critical systems from cybersecurity threats.
- T6. **The cloud:** the cloud can be used for increased data sharing and for offering data-driven services.
- T7. **Additive manufacturing:** produce small batches (or individual) customized products, reduce/eliminate transport distances and lower raw material consumption.
- T8. **Augmented reality:** provide workers and users real-time information for improving decision making and learning/training.
- T9. **Big data and related analytics:** the collection and comprehensive evaluation of data from many different sources.

4. Smart design engineering features

A description of the identified features is then proposed, after analyzing their relation to the 4th IR's environment and technologies.

4.1. Design for empowered users/customers

Customer empowerment can happen either during the final product configuration definition or during the production process (Pessoa & Jauregui-Becker 2020). The former requires the designing of building blocks instead of finalized products and the latter means exploring the possibility that the customers produce themselves the final products.

The design of building blocks, which can be a mix of physical, software and service components require a deep understanding of the problem space in which solutions will be configured. In this sense the design of product configurators, which allow the selection of the desired product options, also plays an important role, since it should be easy to use by the target users. Companies like Tylko¹ have business models completely based on that. Meta products (Rubino *et al.* 2012) consisting of physical and web elements also can deliver this empowerment. While this feature can benefit from changeable products and continuous product development, it supports mass individualization. In terms of technologies, it requires the cloud and can be boosted by configurators that use augmented reality, Philips professional monitors is one example of that.²

Empowering the user and make them capable of product production themselves requires both the cloud and additive manufacturing. By using 3D printers or Distributed Manufacturing Systems (DMS) (Srai *et al.* 2016), the customer can own the manufacturing process. This empowerment though requires customer informing and educating, the availability of user-friendly process and/or tools, and a flexible and viable producing capacity.

¹www.tylko.com

²<https://www.philips.co.uk/p-m-pr/professional-displays/innovations/arc>

4.2. Design for product in use feedback

The functions for in use product feedback must be defined since the beginning of the design process (Pessoa & Jauregui-Becker 2020). These functions relate to knowing the product's actual performance and condition, which might give insight for updating or upgrading the product/service to continuously better serve each individual user and for determining a tailored maintenance strategy (Dawid *et al.* 2017). Another application is for better verification and validation, which is the case of living labs (Mulder *et al.* 2015).

Sensing and communicating capabilities should not be something added on, but the solution should be already designed with integrated sensors (Lehmhus *et al.* 2016). This feature is boosted by products with higher autonomy, which can give more insightful feedback, and require the cloud and IoT availability. Additive manufacturing allows components being printed with embedded sensors. While use information exchange is performed without user awareness, it requires user consent and data privacy guarantee (cybersecurity). The development team must therefore be aware and concerned about ethical, privacy and user data confidentiality issues.

4.3. Design for changeability

Changeable products are those which its modules have built-in robustness against small use variations, adaptability to different use experiences and new technologies, and flexibility to updating and upgrading (Richter *et al.* 2010; Xue *et al.* 2012). In this sense, the designers need understanding what might drive future changes in the product, and then deciding on changeable solution architectures. It requires educating the designers about options design and on (i) defining which options to include in the product; (ii) deciding whether and when exercising the options; (iii) managing the added variants. Once the modularization strategy can segregate the more likely changes into specific modules and thus allowing the maintaining of the remaining system, it might also contribute to reducing resources consumption (Pessôa & Becker 2017).

While changeable products can facilitate mass individualization, they can also benefit from sensing and responding capabilities, which might lead to better robustness gains changes. Several 4th IR technologies can increase changeability. On the one hand, designers can make use autonomy, IoT and the cloud support more adaptable and robust solution. On the other hand, big data and analytics and additive manufacturing allow identifying the options to offer and the quick production of replacing/upgrading parts, respectively. Regardless the case, the concerns with cybersecurity are also present.

4.4. Design for data analytics

Design can take benefit from the sheer amount of available data: (i) physical and virtual product (i.e., digital twins) data; (ii) external data, including information made available for free on the Internet, and which can be accessed using search engines, recommender systems and e-commerce; and (iii) enterprise data from customer relationship management systems and other platforms (Porter & Hoppelmann 2014; Dawid *et al.* 2017). The cloud, IoT enabled cyber physical

systems, simulation, and horizontal and vertical systems integration are some technologies that support accessing the necessary and available data.

It is necessary to design the functions for this big data analysis and include all the necessary cyber security measures. Defining the data provision project becomes central to the design process, also including the opportunity of getting additional information in form a digital twin (Abramovici *et al.* 2016; Thoben & Lewandowski 2016). This brings the need of a design team educated on data modelling and data analytics, including artificial intelligence approaches.

4.5. Design for cyber security

The 4th IR use of cyber physical systems and the central role of data, vertical and horizontal data integration and exchange, and data analytics bring the cyber world challenges, such as viruses and hackers, to the physical world. The design engineering should, therefore, guarantee data security, by ensuring safety, security, privacy and knowledge protection (Reiner 2014). It means security must be embedded as a first principle in product design and across the value chain (Borgia 2014; Porter & Heppelmann 2015). It requires that the design team has members educated on IT related topics, which understand the advantages and vulnerabilities (cyber threats) of adding software and IoT to the designed solutions, and the possible countermeasures to be designed-in (Pessoa & Jauregui-Becker 2020). At the extent of data exchange is used, systems designed for cyber security can better perform functions related to sensing and responding, autonomy and configuration to individual needs.

4.6. Design for (emotional) interaction

When first describing this feature, Pessoa & Becker (2020) included two points:

1. By adding communication capabilities, smart products might interface and collaborate with other smart products in an environment and exploit synergies; and
2. By bridging the interface gap between the technology and the user, the product could be designed not only to providing functionality, but to trigger the right emotional response and create emotional bounds between user and product, which is potentially stronger the more interactive, adaptive and “intelligent” the device is.

Regardless the case, cybersecurity is a critical concern, particularly in terms of preventing interfering with the data characteristics³: accuracy and precision; legitimacy and validity; reliability and consistency; timeliness and relevance; completeness and comprehensiveness; availability and accessibility; and granularity and uniqueness.

For designing the right interaction, the design team should master not only the technical sciences, but also the social sciences. Ethics and privacy aspects and regulations should also be taken into consideration. New failure modes could arise from this interaction and must be analyzed during the design. Especial attention should be given to machine learning, where products can learn from specific usage

³<https://www.blazent.com/seven-characteristics-define-quality-data/>

patterns and deliver better use experience while avoid undesired user feedback, regardless the situation that arises (Pessoa & Jauregui-Becker 2020).

Design for smart collaboration

It requires that smart products are designed to autonomously become aware of the other smart products the co-exist in the vicinity and set collaboration protocols. In this case, common language that establishes standards for interacting is needed (Dawid *et al.* 2017).

Design for emotional interaction

Creating emotional interaction imply new engineering strategies, which calls for participatory analysis and design of systems and services that are: (i) manageable, tailorable, trustworthy, fault tolerant, accountable; (ii) capable of learning from user's behavior; (iii) self-determined usable and controllable by the users; and (iv) compatible with non-networked systems and services (as well as dropouts) (Broy *et al.* 2012).

4.7. Continuous engineering supported by MBSE

Continuous engineering builds on simultaneously considering all engineering disciplines and on the foundation of systems engineering practices by persistently applying engineering tools, methods, and techniques to address change and close gaps between design models and requirements (Iordache 2017). In this scenario, MBSE supports new product design processes that integrate design methods in which the designers, hindering mutual understanding in communication through documented interactions and interfaces between the various disciplines, along with operational issues such as privacy (Hehenberger *et al.* 2016). Tools that support MBSE modelling languages such as the Systems Modelling Language (SysML) allow the traceability and simulation (verification) of system's models. The integration with other tools like PLM systems facilitated the creation of digital twins.⁴

4.8. System lifecycle management

System lifecycle Management (SysLM) concept extends the notion form PLM to all disciplines involved in an engineering solution through its complete lifecycle. Being a concept rather than a tool, SysLM require the vertical and horizontal integration/information exchange among the tools used by the diverse engineering disciplines (Eigner *et al.* 2014). The integrated tools solution should be dynamically adaptable reflecting the ongoing changes of data models (including hardware, software and services perspectives) and capable of determining the cross-impact of changes among these perspectives (Morris *et al.* 2016; Gerhard 2017). PLM and CAD/CAM tools, which must ensure that information from different domains and lifecycle phases is logically and dynamically linked according to both technical and business relations (i.e., artificial intelligence in PLM). Consequently, SysLM integrated data supports better autonomous production, and guarantees the

⁴<https://www.aras.com/en/resources/all/ace-europe-unified-ebom-and-configured-digital-twin-with-leonardo>

performance from the possible variations of individualized and/or changeable products (Pessoa & Jauregui-Becker 2020).

4.9. Increased stakeholder quantity and complexity

Product's and PSS' smartness features, such as autonomy, human-like interaction, ability to cooperate, reactivity, adaptability, or multi-functionality may play a role, requires reshaping the product concept with all participating and involved processes, and taking into account the lifecycle view (Eigner *et al.* 2013; Dawid *et al.* 2017).

The complete lifecycle must be considered while designing and developing smart products and PSS. This requires collaboration with several stakeholders, such as the ones that can give insight on market, technology, legal, sociological, psychological (emotional interaction) and environmental aspects. These stakeholders must be identified, and scenarios created in order to estimate how their needs might evolve through the time. It allows the development of flexible, resilient, lasting, and sustainable solution (Pessoa & Jauregui-Becker 2020).

4.10. Changes in quality perception

Quality perception is becoming rather dependent of personalized goals and experiences than on features generally accepted by the target market. Unique design, safety, quick availability and personalized services are gaining higher importance, once intelligent manufacturing, robotization, and 3D printing are commoditizing manufacturing quality (Hyun Park *et al.* 2017). Human centered design and design for well-being are candidates for involving the human perspective in all steps of the problem-solving process and thus addressing the core needs of those who experience the problem.

Personalized solutions offered might require individualized approaches for lifecycle-long quality control and assurance, thus expanding quality modelling and engineering standards with: (i) models for quality in use, quality of service, compliance, technical and organizational models and methods for quality assurance; (ii) elicitation and negotiation of acceptance requirements and corresponding system concepts (e.g., governance and fairness) (Broy *et al.* 2012).

Another aspect to be taken into account is the concern about privacy and data security (Borgia 2014; Porter & Heppelmann 2015). In a broader scope, introducing the concept of smart products throughout the manufacturing value chain, and (Hyun Park *et al.* 2017) getting the related benefits, will improve the product quality by integrating intelligent specifications and just-in-time information handling throughout the value chain (Duffy *et al.* 2016). Finally, sampling inspection, which has been widely used in the past, is being steadily replaced by total inspection.

4.11. Workers as knowledge finders and processing experts

Design engineers are knowledge workers and their job mainly involve handling and using information. The fast pace of knowledge creation, which is more and more readily available and easy to access is changing the design engineers' skillset. Instead of knowledge accumulators, they must be good at knowledge finding, selecting, combining and using (Rozkwitalska & Slavik 2017). Creative design techniques such as TRIZ and axiomatic design can play an important role, since

they provide approaches for better using the available knowledge to define new solutions (Cavallucci & Eltzer 2011).

Horizontal and vertical systems integration, the cloud, and big data and related analytics are also technologies that allow reaching and combining the data available. In this context, augmented reality can be used to provide the resulting information in a just-in-time fashion (Ras *et al.* 2017; Caldarola *et al.* 2018).

4.12. Open and social low-cost innovation

Open innovation is considered a fundamental concept from Industry 4.0. (Lasi *et al.* 2014) In this way, the design processes should take advantage from the knowledgeable and creative individuals outside the company, which can also contribute to achieving strategic goals and reducing innovation costs, and that sharing intellectual property both ways is useful for different parties in different ways. Together with crowdsourcing, cloud-based design and manufacture, and mass collaboration, open Innovation compose what is called Social Product Development, which enable innovation through collaborating communities (Bertoni *et al.* 2012; Forbes & Schaefer 2017). Social Product Development relies on the cloud and requires secure information channels.

5. Discussion on the features

When designing a development process, the three key dimensions are the choice of methods and procedures, the required knowledge and skills from the people that will perform the process, and the availability of the right infrastructure and tools for supporting the process execution (SEI 2010). The before mentioned features were therefore analyzed according their specific impact on the procedures, people and tools (Table 4).

Figure 5 shows how the smart design engineering features impact the can leverage the product design and development to exploiting the benefits from the 4th IR. Therefore, process improvement projects could use it as guidelines.

6. Summary and conclusion

Leveraging the PDDP to better exploiting the 4th IR benefits calls for evolutions in design engineering. In this context, smart design engineering was here defined as a methodology used during the analysis and design of a product or a system, which can be composed by hardware, software and/or services (therefore not limited to designing smart products), and that explicitly considers exploiting the technologies and opportunities from the 4th IR.

A set of smart design engineering features was identified based on the literature and on the feedback from 25 researchers/practitioners. Further analysis was conducted to understand the relation among the features, the 4th IR's core technologies and the several business and market changes resulting from the 4th IR. This analysis led to a set composed by 12 features, which impact on the PDDP' key dimensions (procedures, people and tools) was identified. Assuming a generic PDDP and covering the solution's complete life cycle, the identified features' impact was mapped to the PDDP's phases. Therefore, this work's objective was achieved.

Table 4. Features impact on the PDD process, people and tools.

Impact on the process, people and tools

F1	<p>1.1 (procedure) Design the configuration process considering the users' needs and limitations to interacting with technology.</p> <p>1.2 (procedure) Design of flexible building blocks rather than a final product.</p> <p>1.3 (procedure) Explore of designs choices compatible to 3D printing.</p> <p>1.4 (tools) Easy to use configurators, which might include augmented reality.</p>
F2	<p>2.1 (procedure) The product feedback type and content should be defined in the conceptual design.</p> <p>2.2 (procedure) Consider designing and producing (3D printed) the solution with integrated sensors.</p> <p>2.3 (procedure) Consider the use of Living labs as an alternative for verification and validation.</p> <p>2.4 (people) Arise the development team's awareness and concern about ethical, privacy and data confidentiality issues.</p> <p>2.5 (tools) The tools chosen to support get in use feedback require cyber secure data exchange channels.</p> <p>2.6 (tools) Additive manufacturing capability is needed for 3D printing parts with embedded sensors.</p>
F3	<p>3.1 (procedure) The decision about changeability should be taken during the conceptual design.</p> <p>3.2 (procedure) The solution's architecture should be designed to accommodate the foreseen future changes.</p> <p>3.3 (procedure) Design ways to perceive a change is needed, so the product can adapt to new situations.</p> <p>3.4 (people) Knowledge about modularization strategies to handle changes and to design options.</p> <p>3.5 (tools) Modelling tools that support designing product variants and forecasting change impact across the variants.</p>
F4	<p>4.1 (procedure) In order to guarantee that the right data will be available, the digital twin and related data models should be designed in parallel to the physical product design.</p> <p>4.2 (procedure) The designer should take advantage from information made available for free on the Internet.</p> <p>4.3 (people) Knowledge on data modelling.</p> <p>4.4 (tools) Data modelling and data analytics tools.</p>
F5	<p>5.1 (procedure) Cybersecurity guidelines and best practices should be talking into account during all design phases, failure modes identification and solution testing.</p> <p>5.2 (people) Knowledge on cyber threats and cyber security measures.</p> <p>5.3 (tools) Cybersecurity testing tools.</p>
F6	<p>6.1 (procedure) Design not only the user regular journey, but also the emotional journey.</p> <p>6.2 (procedure) Define the possible ways for trusting and collaborating with other smart products.</p> <p>6.3 (procedure) Analyse the possible failure modes that might arise from the collaboration with other smart products and from triggering user emotional reaction.</p> <p>6.4 (people) Knowledge about ethics, privacy regulations and possible related issues.</p> <p>6.5 (people) Knowledge about artificial intelligence and machine learning.</p> <p>6.6 (people) Knowledge on social sciences, particularly on behavioral sciences.</p>

Table 4. Continued

Impact on the process, people and tools

F7	7.1 (procedure) Use modelling languages that support MBSE. 7.2 (people) Knowledge of modelling languages that support MBSE. 7.3 (tools) Have modelling tools that support MBSE languages and that integrate with other tools, also allowing system life cycle management.
F8	8.1 (people) Knowledge on how to integrate and make use of the information available from the diverse tools. 8.2 (tools) Tools capable of exchanging the solution data through its life cycle.
F9	9.1 (procedure) Include techniques for listening, capturing and balancing conflicts among the voice from the different stakeholders (and not only the customer). 9.2 (people) Awareness of the stakeholder's multiplicity, which might impact or be impacted by the developed solution. 9.3 (tools) Tools capable of requirements documenting, prioritizing and traceability from conceptual to detail design.
F10	10.1 (procedure) Lean and agile product design and development process. 10.2 (procedure) Include quality modelling and engineering standards with models for quality in use, quality of service, compliance, technical and organizational models and methods for quality assurance. 10.3 (procedure) Design products with built-in quality assurance functionalities. 10.4 (people) Wide awareness of the stakeholders' quality expectations. 10.5 (tools) Have total inspection capacity.
F11	11.1 (procedure) Explicitly include guidelines for knowledge finding and validation/acceptance. 11.2 (procedure) Incorporate creative design techniques, such as TRIZ and axiomatic design. 11.3 (people) Receive the necessary training on creative design techniques. 11.4 (tools) Provide means for effective patent databases search.
F12	12.1 (procedure) Include decision criteria for defining when and which social product development approach is applicable. 12.2 (people) Receive the necessary training on social product development approaches.

This work contributes to both design theory and practice: (i) it deepens the understanding about the necessary smart design engineering features and show these features impact on the design and development process's (PDDP) key dimensions (procedures, people and tools); (ii) it maps the features' impact on PDDP's phases, thus providing practical direction for process improvement, which lead to better benefiting from the 4th IR opportunities.

Despite its contributions, this study has some limitations, particularly because the topic is recent and still under development. Although the features identification was based on the literature and expert opinion, no reference was found, which showed the combined use of all or even most of the features. Future research on applying the combined features and documenting the resulting PDDP actual benefits and challenges is still needed. Further research opportunities also include the need of further education and new tools and techniques that tackle the features impact in each PDDP phase.

Planning	Concept Development	System-level Design	Detail Design	Testing and Refinement	Production Ramp-up	Product/ Process Follow-up	End-of-life/ End-of-offering
(9.2)	(1.1) (2.1)	(1.2) (3.2)	(1.3) (2.2)	(2.3) (4.2)	(1.4) (2.2)	(2.5) (7.3)	(8.1) (8.2)
(10.2)	(3.1) (4.2)	(3.3) (3.4)	(3.5) (4.1)	(5.1) (5.3)	(2.4) (2.6)	(8.1) (8.2)	
(10.3)	(5.1) (5.2)	(3.5) (4.1)	(4.2) (4.3)	(7.1) (7.2)	(8.1) (8.2)		
(12.1)	(6.1) (6.4)	(4.2) (4.3)	(4.4) (5.1)	(7.3) (8.1)	(10.5)		
(12.2)	(6.5) (6.6)	(4.4) (5.1)	(5.2) (6.2)	(8.2) (9.3)			
	(7.1) (7.2)	(5.2) (6.1)	(6.3) (6.4)				
	(7.3) (8.1)	(6.2) (6.3)	(6.5) (6.6)				
	(8.2) (9.1)	(6.4) (6.5)	(8.1) (8.2)				
	(9.2) (9.3)	(6.6) (7.1)	(9.3) (10.2)				
	(10.2)	(7.2) (7.3)	(10.3) (10.4)				
	(10.4)	(8.1) (8.2)	(11.1) (11.2)				
	(11.1)	(9.1) (9.2)	(11.3) (11.4)				
	(11.2)	(9.3) (10.2)					
	(11.3)	(10.3) (10.4)					
	(11.4)	(11.1) (11.2)					
		(11.3) (11.4)					

Figure 5. Features impact and the PDDP.

References

- Abramovici, M., Göbel, J. C. & Savarino, P. 2016 Virtual twins as integrative components of smart products. *IFIP Advances in Information and Communication Technology* **492**, 217–226; doi:10.1007/978-3-319-54660-5_20.
- Bertoni, M., Larsson, A., Ericson, Å., Chirumalla, K., Larsson, T., Isaksson, O. & Randall, D. 2012 The rise of social product development. *International Journal of Networking and Virtual Organisations* **11** (2), 188–207; doi:10.1504/IJNVO.2012.048346.
- Borgia, E. 2014 The internet of things vision: key features, applications and open issues. *Computer Communications* **54**, 1–31; doi:10.1016/j.comcom.2014.09.008.
- Broy, M., Cengarle, M. V. & Geisberger, E. 2012 Cyber-physical systems: imminent challenges. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* **7539**, 1–28; doi:10.1007/978-3-642-34059-8_1.
- Caldarola, E. G., Modoni, G. E. & Sacco, M. 2018 A knowledge-based approach to enhance the workforce skills and competences within the Industry 4.0. In *EKNOW 2018: The Tenth International Conference on Information, Process, and Knowledge Management*, Elsevier, Netherlands, pp. 56–61.
- Cavallucci, D. & Eltzer, T. 2011 Structuring knowledge in inventive design of complex problems. *Procedia Engineering* **9**, 694–701; doi:10.1016/j.proeng.2011.03.157.
- Dawid, H., Decker, R., Hermann, T., Jahnke, H., Klat, W., König, R. & Stummer, C. 2017 Management science in the era of smart consumer products: challenges and research perspectives. *Central European Journal of Operations Research* **25** (1), 203–230; doi:10.1007/s10100-016-0436-9.
- Duffy, A., Whitfield, I., Ion, W. & Vuletic, T. 2016 *Smart Products Through-Life: Research Roadmap*. <https://www.strath.ac.uk/media/departments/dmem/research/SmartProductsThroughLife.pdf>.
- Eigner, M., Dickopf, T., Apostolov, H., Schaefer, P., Faißt, K. G., Kefler, A. 2014 System Lifecycle Management: Initial Approach for a Sustainable Product Development Process Based on Methods of Model Based Systems Engineering. In: Fukuda S., Bernard A., Gurumoorthy B., Bouras A. (eds) *Product Lifecycle Management for a Global Market*.

- PLM 2014. *IFIP Advances in Information and Communication Technology*, vol 442. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-45937-9_29.
- Eigner, M., Schäfer, P. D. & Apostolov, H. 2013 Leveraging product development for a sustainable future: energy and resource efficiency in lifecycle analysis. In *Smart Product Engineering* (ed. M. Abramovic & R. Stark), pp. 725–734. Springer-Verlag; doi: [10.1007/978-3-642-30817-8_71](https://doi.org/10.1007/978-3-642-30817-8_71).
- Forbes, H. & Schaefer, D. 2017 Social product development: the democratization of design, manufacture and innovation. *Procedia CIRP* 60, 404–409; doi:[10.1016/j.procir.2017.02.029](https://doi.org/10.1016/j.procir.2017.02.029).
- Gerhard, D. 2017 *Multi-Disciplinary Engineering for Cyber-Physical Production Systems*, pp. 89–110. Springer; doi:[10.1007/978-3-319-56345-9](https://doi.org/10.1007/978-3-319-56345-9).
- Hehenberger, P., Vogel-Heuser, B., Bradley, D., Eynard, B., Tomiyama, T. & Achiche, S. 2016 Design, modelling, simulation and integration of cyber physical systems: methods and applications. *Computers in Industry* 82, 273–289; doi:[10.1016/j.compind.2016.05.006](https://doi.org/10.1016/j.compind.2016.05.006).
- Hermann, M., Pentek, T. & Otto, B. 2016 “Design principles for industrie 4.0 scenarios,” 2016 49th Hawaii International Conference on System Sciences (HICSS), Koloa, HI, 2016, pp. 3928–3937, doi: [10.1109/HICSS.2016.488](https://doi.org/10.1109/HICSS.2016.488).
- Hyun Park, S., Seon Shin, W., Hyun Park, Y., & Lee, Y. 2017 Building a new culture for quality management in the era of the Fourth Industrial Revolution. *Total Quality Management & Business Excellence* 3363, 1–12; doi:[10.1080/14783363.2017.1310703](https://doi.org/10.1080/14783363.2017.1310703).
- Iordache, O. 2017 *Implementing Polytope Projects for Smart Systems*. Vol. 92, pp. 139–157. Springer; doi:[10.1007/978-3-319-52551-8](https://doi.org/10.1007/978-3-319-52551-8).
- Lasi, H., Fettke, P., Kemper, H. G., Feld, T. & Hoffmann, M. 2014 Industry 4.0. *Business and Information Systems Engineering* 6 (4), 239–242; doi:[10.1007/s12599-014-0334-4](https://doi.org/10.1007/s12599-014-0334-4).
- Lee, I. & Lee, K. 2015 The internet of things (IoT): applications, investments, and challenges for enterprises. *Business Horizons* 58 (4), 431–440; doi:[10.1016/j.bushor.2015.03.008](https://doi.org/10.1016/j.bushor.2015.03.008).
- Lehmhus, D., Aumund-Kopp, C., Petzoldt, F., Godlinski, D., Haberkorn, A., Zöllmer, V. & Busse, M. 2016 ScienceDirect customized smartness: a survey on links between additive manufacturing and sensor integration. *Procedia Technology* 26 (26), 284–301; doi: [10.1016/j.protcy.2016.08.038](https://doi.org/10.1016/j.protcy.2016.08.038).
- Lu, Y. 2017 Industry 4.0: a survey on technologies, applications and open research issues. *Journal of Industrial Information Integration* 6, 1–10; doi:[10.1016/j.jii.2017.04.005](https://doi.org/10.1016/j.jii.2017.04.005).
- Luchs, M. G., Swan, K. S. & Creusen, M. E. H. 2016 Perspective: a review of marketing research on product design with directions for future research. *Journal of Product Innovation Management* 33 (3), 320–341; doi:[10.1111/jpim.12276](https://doi.org/10.1111/jpim.12276).
- MacDougall, W. 2014 Industrie 4.0 – smart manufacturing for the future. GTIA – Germany Trade and Invest, 40; doi:[10.1007/978-3-642-36917-9](https://doi.org/10.1007/978-3-642-36917-9).
- Mehrsai, A., Henriksen, B., Røstad, C. C., Hribernik, K. A. & Thoben, K. D. 2014 Make-to-XGrade for the design and manufacturing of flexible, adaptive, and reactive products. *Procedia CIRP* 21, 199–205; doi:[10.1016/j.procir.2014.03.147](https://doi.org/10.1016/j.procir.2014.03.147).
- Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., Sauer, O., Schuh, G., Sihn, W. & Ueda, K. 2016 Cyber-physical systems in manufacturing. *CIRP Annals – Manufacturing Technology* 65 (2), 621–641; doi:[10.1016/j.cirp.2016.06.005](https://doi.org/10.1016/j.cirp.2016.06.005).
- Morris, A., Setchi, R. & Prickett, P. 2016 Product change management and future information architectures. *Smart Innovation, Systems and Technologies* 52, 241–250; doi:[10.1007/978-3-319-32098-4_21](https://doi.org/10.1007/978-3-319-32098-4_21).
- Mulder, I., Van Doorn, F. & Stappers, P. J. 2015 Co-creation in context: the user as co-creator approach. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* 9189, 74–84; doi:[10.1007/978-3-319-20804-6_7](https://doi.org/10.1007/978-3-319-20804-6_7).

- Pessoa, M. & Jauregui-Becker, J. 2020 Smart design engineering: a literature review of the impact of the 4th industrial revolution on product design and development. *Research in Engineering Design* **31**, 175–195; doi:[10.1007/s00163-020-00330-z](https://doi.org/10.1007/s00163-020-00330-z).
- Pessôa, M. V. P. & Becker, J. M. J. 2017 Directives to support the design of changeable (I) PSS. In *Proceedings of the International Conference on Engineering Design, ICED, 3* (DS87-3). The Design Society, Glasgow, Scotland, UKp. 121–130.
- Porter, M. E. & Heppelmann, J. E. 2014 How smart, connected products are transforming competition. *Harvard Business Review* November 2014 64–89; doi:[10.1017/CBO9781107415324.004](https://doi.org/10.1017/CBO9781107415324.004).
- Porter, M. E. & Heppelmann, J. E. 2015 How smart, connected products are transforming companies. *Harvard Business Review* **2015**; October 2015 doi:[10.1017/CBO9781107415324.004](https://doi.org/10.1017/CBO9781107415324.004).
- Ras, E., Wild, F., Stahl, C. & Baudet, A. 2017 Bridging the skills gap of workers in industry 4.0 by human performance augmentation tools – challenges and roadmap. In *ACM International Conference Proceeding Series, Part F1285*, ACM - Association for Computing Machinery pp. 428–432; doi:[10.1145/3056540.3076192](https://doi.org/10.1145/3056540.3076192).
- Reeves, M., Bergman, R., Gourévitch, A. & Ortiz, M. 2016 *Forks in the Road: Navigating Industry Disruption*. <https://www.bcgperspectives.com/content/articles/business-unit-strategy-forks-road-navigating-industry-disruption/>.
- Reiner, A. 2014 Industrie 4.0 - Advanced Engineering of Smart Products and Smart Production October 2014 Conference: 19th International Seminar on High Technology (Piracicaba, Brasil October 9th, 2014) At: Methodist University of Piracicaba Lab. for Computer Integrated Design and Manufacturing <http://www.unimep.br/scpm> Rod. Luis Ometto (SP 306), Km 24 13451-900 Santa Barbara d'Oeste, SP - Brazil Volume: Proceedings 19th International Seminar on High Technology Technological Innovations in the Product Development.
- Richter, A., Sadek, T. & Steven, M. 2010 Flexibility in industrial product-service systems and use-oriented business models. *CIRP Journal of Manufacturing Science and Technology* **3** (2), 128–134; doi:[10.1016/j.cirpj.2010.06.003](https://doi.org/10.1016/j.cirpj.2010.06.003).
- Rodríguez-Mazahua L, Rodríguez-Enríquez CA, Sánchez-Cervantes JL, Cervantes J, García-Alcaraz JL, Alor-Hernández G (2016) A general perspective of Big Data: applications, tools, challenges and trends. *J Supercomput* **72**(8):3073–3113. <https://doi.org/10.1007/s11227-015-1501-1>.
- Rozkwitalska, M. & Slavik, J. 2017 Around learning and industry 4.0 in management theory. *International Journal of Contemporary Management* **16** (4), 185–206; doi:[10.4467/24498939ijcm.17.044.8267](https://doi.org/10.4467/24498939ijcm.17.044.8267).
- Rubino, S. C., Hazenberg, W. & Huisman, M. 2012 *Meta Products Meaningful Design For Our Connected Worlds*. BIS Publishers.
- Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P. & Harnisch, M. 2015 Industry 4.0: the future of productivity and growth in manufacturing industries. *The Boston Consulting Group*, pp. 1–20. https://www.bcgperspectives.com/Images/Industry_40_Future_of_Productivity_April_2015_tcm80-185183.pdf.
- SEI. 2010 CMMI® for Development, Version 1.3 (CMMI-DEV, V1.3). In *Software Engineering Institute*. <https://doi.org/CMU/SEI-2010-TR-033> ESC-TR-2010-033.
- Srai, J. S., Kumar, M., Graham, G., Phillips, W., Tooze, J., Ford, S., Beecher, P., Raj, B., Gregory, M., Tiwari, M. K., Ravi, B., Neely, A., Shankar, R., Charnley, F. & Tiwari, A. 2016 Distributed manufacturing: scope, challenges and opportunities. *International Journal of Production Research* **54** (23), 6917–6935; doi:[10.1080/00207543.2016.1192302](https://doi.org/10.1080/00207543.2016.1192302).

- Thoben, K. D. & Lewandowski, M.** 2016 Information and data provision of operational data for the improvement of product development. *IFIP Advances in Information and Communication Technology* **467**, 3–12; doi:[10.1007/978-3-319-33111-9_1](https://doi.org/10.1007/978-3-319-33111-9_1).
- van Rhijn, G. & Bosch, T.** 2017 Operator-oriented product and production process design for manufacturing, maintenance and upgrading. In *Dynamics of Long-Life Assets* (ed. S. N. Grösser), pp. 133–149. Springer; doi:[10.1007/978-3-319-45438-2_8](https://doi.org/10.1007/978-3-319-45438-2_8).
- Verzijl, D., Dervojeda, K., Jorn, S.-K.-F., Nagtegaal, F., Probst, L. & Frideres, L.** 2014 *Smart Factories Capacity optimisation*. **26**, 17.
- Wang, S., Wan, J., Li, D. & Zhang, C.** 2016 Implementing smart factory of industrie 4.0: an outlook. *International Journal of Distributed Sensor Networks* **12** (1); October 2015 doi:[10.1155/2016/3159805](https://doi.org/10.1155/2016/3159805).
- Wang, S., Wan, J., Zhang, D., Li, D. & Zhang, C.** 2015 Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination. *Computer Networks* **101**, 158–168; doi:[10.1016/j.comnet.2015.12.017](https://doi.org/10.1016/j.comnet.2015.12.017).
- Ward, A., Liker, J. K., Cristiano, J. J. & Sobek, D. K.** 1995 The second Toyota paradox: how delaying decisions can make better cars faster. *Sloan Management Review* **36** (3), 43–61; doi:[10.1016/0024-6301\(95\)94310-U](https://doi.org/10.1016/0024-6301(95)94310-U).
- Wolfgang Maass, S. J.** 2007 Dynamic product interfaces: a key element for ambient shopping environments. In *20th BLED Conference*. Publisher Faculty of Organizational Sciences, Bled, Slovenia Maass, Wolfgang & Janzen, Sabine: Dynamic Product Interfaces: A Key Element for Ambient Shopping Environments. 2007. - 20th Bled eConference "eMergence: Merging and Emerging Technologies, Processes, and Institutions". - Bled, Slovenia. <http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.124.5224>.
- Xue, D., Hua, G., Mehrad, V. & Gu, P.** 2012 Optimal adaptable design for creating the changeable product based on changeable requirements considering the whole product life-cycle. *Journal of Manufacturing Systems* **31** (1), 59–68; doi:[10.1016/j.jmsy.2011.04.003](https://doi.org/10.1016/j.jmsy.2011.04.003).