



Smart design engineering: a literature review of the impact of the 4th industrial revolution on product design and development

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Abstract

Industrial revolutions (IRs) are mostly associated with how transformations regarding the operations of an enterprise affect said enterprise's manufacturing systems. However, the impact of these transformations exceeds the production systems themselves; rather, they affect the entire value chain, from the product design and development process (PDDP) through manufacturing and supply-chain management to marketing and disposal. As the new PDDP to a large extent defines the value chain for a company, the challenge lies in ensuring that the designed product will help the company fully benefit from the IRs. By analysing the 4th IR, the authors reveal that few publications shed light on this aspect. Consequently, the purpose of this study is to establish features and properties that will shape the PDDP throughout the 4th IR and into a smart design engineering. To accomplish this, the authors conduct a systematic review of the literature, which provides ten findings. These findings are then analysed by 11 specialists both from academia and the industry, and the findings' relations to the 4th IR and their impact on the product development process is discussed. By establishing these findings, this paper provides a platform for the understanding of what could potentially shape smart design engineering and its design-related activities.

Keywords Smart design engineering · 4th Industrial Revolution · Industrie 4.0 · Industry 4.0 · Smart industries · Product design and development

1 Introduction

While the 1st, 2nd and 3rd industrial revolutions (IRs) changed the industries' shop floors through the use of steam power, electrical power and automation, respectively, the 4th IR is about the communication among cyber-physical systems (CPSs) (Schwab 2016). Here, the advances of computing power, intelligent control and connectivity not only lead to the development of smart products but also allow for radical changes in several other areas. As in the previous IRs, sweeping changes in the shop floor are causing a cascading effect of changes through all the processes in the value chains, thus supporting the creation of new business models and allowing for the production of improved products, which are impacting customers' uses and behaviours in new ways.

A research study performed by the Boston Consulting Group (BCG) (Rüßmann et al. 2015a) shows that in Germany alone, starting in 2016, this revolution will contribute approximately 1% per year to the gross domestic product (GDP) for over 10 years. Furthermore, 85% of the respondents from another global survey also conducted by the BCG—a study in which more than 750 production managers from leading companies in several industrial sectors were interviewed—believe they can benefit from implementing elements resulting from the 4th IR into their own processes (Küpper et al. 2016). Indeed, this new production paradigm is disrupting almost every industry in every country (Schwab 2016). The success of this industrial disruption, however, requires new products and business models that can adjust to the rapidly changing market conditions (Reeves et al. 2016).

Although smart factories can better support the manufacturing of individualised products and the avoidance of sub-optimum use of their resources (Verzijl et al. 2014; Wang et al. 2015), and smart products have the potential to better serve the needs of its customers through information exchange and adaptiveness (Maass and Janzen 2007; Porter and Heppelmann 2014), these benefits are only achieved

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if the products are designed accordingly (Rüßmann et al. 2015b). One of the characteristics of smart products is their autonomic self-properties, such as self-configuration, self-monitoring and self-healing (Thames and Schaefer 2017). Consequently, a new product development approach is required that fully exploits CPS' data processing and communication capacities, which, when added to the internet of things (IoT), data and services, allow for autonomous properties and support continuous feedback from both products and services in the field (Lee and Lee 2015; Monostori et al. 2016). Product development should, therefore, 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 and Heppelmann 2014).

In our practical experience, by taking part in several meetings organised by the Dutch Smart Industry initiative,¹ a recurrent question from the participant companies is 'what does the 4th IR mean to product design and development?' While working to answer this question, scarce literature was found that approaches this issue, particularly considering the product development process (PDP) as a whole. Shafiq et al. (2015) present the virtual engineering object (VEO), which embeds all the necessary information for describing and creating an engineering artefact, but they do not give detailed information about the VEO design process. Hermann et al. (2016) conduct a thorough literature review on the design principles for Industry 4.0; in their case, the objects of design were Industry 4.0 scenarios, and their work did not address the PDP itself. Similarly, Wang et al. (2016a) compare the Industry 4.0 production system and traditional production line without discussing possible issues related to the development of the products to be produced. Lu (2017) conducts a comprehensive review on the topic but presents no findings about its impact on the engineering design process.

This paper aims to fill this gap by providing an understanding of how the 4th IR impacts product design and development and what features and properties will shape the resulting smart design engineering. The study described here has taken the form of a systematic literature review. The methodology consists of searching multiple databases using a wide range of keywords and phrases associated with the 4th IR, such as Industry 4.0, Industrie 4.0, smart industry, smart product and design. The relevant identified articles are reviewed; from these reviews the authors compile a set of key findings regarding which the literature is consistent. The findings are further analysed by 11 specialists from both academia and the industry, and the findings' relations to the

4th IR and the impact on the PDP is discussed. By establishing these findings, this paper provides a state-of-the-art review of work on this topic and thus provides a platform for understanding what smart design-engineering entails and its design-related activities.

Although the term Industrie 4.0 (Industry 4.0) was originally the German term for the 4th IR, its popularity made it difficult to differentiate the two; they are, however, two different terms. While Industry 4.0 focuses on the communication among CPSs and its impact on the shop floor, the 4th IR expands the core concepts of Industry 4.0 by including changes outside of the shop floor (i.e., products, customer attitudes, business models, etc.). It is also important to note that the term Industry 4.0 was coined at the 2011 Hannover Fair, while the 4th IR (as have been previous IRs) is a gradual phenomenon. This explains why this literature review has no starting date restriction and is the reason some of the cited papers were published before the Industry 4.0 hype. The authors decided to use the English translated term (Industry 4.0) rather than the original German term, since the English term appears more in the analysed literature (only papers written in English were analysed).

This paper is structured as follows. Considering the wide impact of the 4th IR and the several dimensions that affect product design and development, Sect. 2 further details the context of this study. Section 3 describes the research methods, finishing with a summary of the initial results of the search for relevant literature. Section 4 presents the analysis of the literature and the paper's key findings. The findings are discussed in Sect. 5, leading to the formulation of a preliminary definition of smart design engineering. Finally, Sect. 6 summarises the work and suggests directions for further research.

2 The industrial revolutions and smart design engineering

This section discusses the impact of the IRs to establish the research context. By understanding how these revolutions helped shape the evolution of new product design and development, it is possible to identify the trends driving smart design engineering.

As in the previous IRs, the changes that triggered the 4th IR on the shop floor led to changes throughout the value chain, supported the creation of new business models and allowed for the design, development and production of improved products. As a result, seven perspectives were chosen by the authors for analysis, and the rationales for these choices are as follows: (1) technology, which is the base for each IR, allows for improved production performance. (2) This improved production performance allows for cost reduction and/or the developing of new products

¹ The Dutch research and development program stimulating national industry to adopt the Industry 4.0 production paradigm.

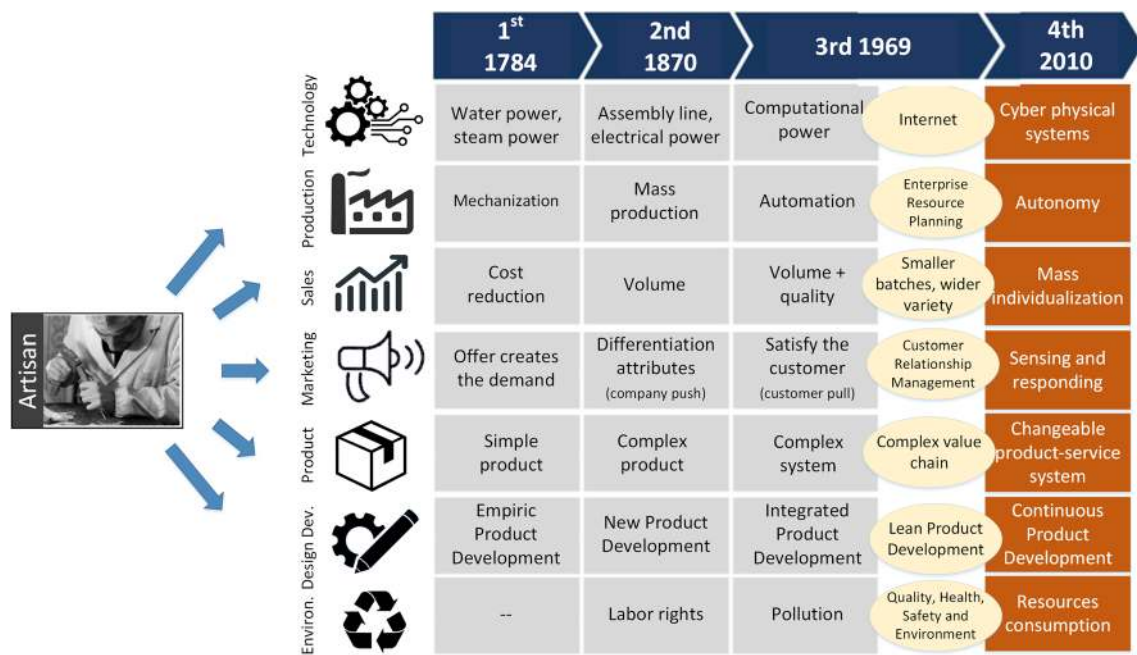


Fig. 1 Changes driven by each industrial revolution

(embedding new technologies, using different materials with tighter tolerances, etc. (3) These new products might better fit the market needs and increase sales. (4) One important constraint regarding what is acceptable in terms of the production processes and the products themselves is society's awareness of its impact in terms of sustainability. Finally, (5) to succeed in the previous four aspects, the products should be designed and developed accordingly.

Figure 1 summarises how the analysed perspectives evolved through each of the four IRs and which were the responsibilities of the artisans in the pre-industrial era. For each perspective, the main aspects are highlighted. In the case of the 3rd IR, some bridging elements to the 4th IR are also included (see the ellipses). These perspectives and aspects are the drivers for establishing the strategy of the literature review, which is presented in the next section. It is important to note that the changes among these perspectives were not completely synchronised, and the beginning and end of each period is not clearly defined. Furthermore, the highlighted dates refer to important industrial milestones that characterise each era. In addition, the figure does not imply that there was a substitution in the perspectives from one revolution to another. For instance, cost reduction is still present, while additional concerns regarding quality and individualisation became more important; similarly, even though product service systems (PSSs) are becoming more relevant in the present day, complex products and systems of systems are still prevalent.

In terms of technology, the 1st IR introduced the use of steam power through the mechanisation of the textile

industry, and the power loom was introduced in 1784. This mechanisation simplified previously laborious tasks and increased the availability of products. In 1870, with the use of electrical power in the first assembly lines in Cincinnati's slaughterhouses, the 2nd IR officially began and flourished in the early twentieth century when Henry Ford began the age of mass production. The 3rd IR emerged due to converging technologies and increased computational power and culminated in the development of the first programmable logic controller (PLC) in 1969, which allowed for the gradual automation of factories. During this period there was also an important development of information systems to support factory production [such as manufacturing resource planning (MRP)] and integrate it into other areas of the company, i.e., enterprise resource planning (ERP) systems (Chen 2001). The popularisation of the Internet led the way to the further integration among systems through the supply chain. Finally, the 4th IR is characterised by communication among CPSs, which resulted in the IoT; indeed, this 'smartness' can be characterised by the communication and collaboration among autonomous CPSs (Park et al. 2017; Porter and Heppelmann 2014). CPSs integrate intelligence-generating technologies, including (i) sensors and/or actuation to either gather data from the environment or to use the data to change the environment, respectively; (ii) computing power for data analysis and (iii) optional interfaces to exchange information with the CPS environment (Dawid et al. 2017). According to Rüßmann et al. (2015), the nine core Industry 4.0 technologies are autonomous robots, simulation, horizontal and vertical system integration, the IoT, cybersecurity, the

cloud, additive manufacturing, augmented reality, big data and related analytics.

In the 1st IR, the lack of available goods made almost anything a sales success, i.e., the supply created the demand. In that production era, the main marketing priority was reducing production cost (Kotler and Keller 2013). The 2nd IR brought further product cost reduction and the economy of scale, where the high earnings resulted from sales volume and the extent to which a product differed from that of one's competitors. In terms of marketing, the 3rd IR was characterised by the realisation that the company's purpose could no longer be to merely manufacture a variety of products but also and primarily had to be customer satisfaction (Kotler and Keller 2013). While factories during the 2nd IR were based on the mass production of identical products, new technologies gradually reduced the cost of producing much smaller batches of a wider variety of products (Markillie 2012); thus, quantity and quality (value pulled by the customer) became the new driver of sales. Customer relationship management (CRM) became standard, where companies engaged in learning the most about and better serving their individual customers.

It is also interesting to note how increasing sales is no longer achieved by only focusing on cost reduction and improved quality but requires products that fulfil individual needs (Wang et al. 2017). As customer relationships became more important, more attention was paid to identifying and developing close collaborations with main stakeholders in the value chain to provide customised solutions on a mass scale (mass individualisation) and create long-term relationships. Haeckel (1995) points out that this is not just about being consumer-oriented but requires companies to collaborate with and learning from customers and adapt to their individual and dynamic needs, where firms move from practising a 'make-and-sell' strategy to a 'sense-and-respond' strategy. Effective sensing and responding requires resilient and changeable product architectures that are (1) robust against small use variations, (2) adaptable to different use experiences and new technologies, and (3) can flexibly to update and upgrade (Richter et al. 2010). CPS characteristics facilitate the incorporation of this sensing and responding and proceeding in the direction of mass individualisation. With a well-planned IoT-aided servitisation strategy, companies are able to create a solid value proposition based on reliable data regarding product usage and performance (Rymaszewska et al. 2017). Moreover, services can be created or tailored to increase profitability and improve customer satisfaction.

In the 2nd IR, the simple products from the 1st IR became more complex than the machines that produced them. Once the products became too complex for only one person to master the entire design process, the evolution of PDDPs towards further division of labour was

required (Kapás 2008); thus, empirical product development evolved into new PDPs that were more structured. World War II's 'war effort' and the following Cold War resulted in rapid technological growth, where products became complex systems. At this moment, integrated product development made it possible to combine the work and information produced by several different actors from diverse fields required to design the product (Andreasen and Hein 2000). The post-WWII environment prompted the 3rd IR. While the victorious nations were engaged in a cold war, the defeated nations, particularly Japan, engaged in a quality revolution that involved doing more with less. Some Japanese companies, notably Toyota, embraced practices that were later defined as lean product design and development. These practices included those similar to those of integrated product development but incorporated a more organic view of the process, particularly in terms of reinforcing the integration of the value pulled by the customer and streamlining the flow not only inside the factory but also through the value chain, including product-related services (Morgan and Liker 2006; Pessoa and Trabasso 2017). Another important design and development trend was towards agility by focusing on the information flow rather than the documentation (Beck et al. 2001; Cohen et al. 2004).

Moreover, the scope of the product expanded beyond physical systems, resulting in design that considered products, services, support systems, business elements and the work flow and the interactions among them. These products are called PSSs (Vasanth et al. 2012). PSSs require a business approach where manufacturing firms' revenue shifts from only selling physical products to also selling services through the PSS lifecycle, where value delivery ranges from more product to more service shares (Alonso-Rasgado et al. 2004; Baines et al. 2007; Meier et al. 2010; Tholke et al. 2001). Simply adding a service to the designed product is no longer sufficient; PSS requires a holistic, integrated view that considers the concurrent design and development of products and services (Baines et al. 2007; Meier et al. 2010).

Through the IRs, the concerns about the factory's impact on the environment also gained importance. Initially, the focus was on workers' labour rights; the repercussion of the death of 146 workers in the Triangle Shirtwaist Factory fire in New York City on 25 March 1911 was a significant push in favour of the definition of new labour laws in the USA (Pence et al. 2003). During the 3rd IR, the concerns went beyond the factory itself and included the pollution it created and how it harmed the surrounding environment and population (Colby 1991; Kasa 2009). Regarding the impact on users, workers, society as a whole and the environment, a wider approach was defined that includes quality, health, safety, and the environment (QHSE) (Van Adrichem and Thomeer 2002).

Nowadays, not only are reusing and recycling materials and products important, reducing the dependency on scarce materials and eliminating material toxicity and the contamination of materials are vital. The remanufacturing and redesign of products and production processes should also be considered to support a circular economy (Tukker 2004). It argues for thinking in terms of self-reinforcing ‘value cycles’ rather than linear value chains, where firms are in a process of continual product, service and value-chain development (Day 1999). Recent directives in Europe (Deloitte 2014) and North America hold manufacturers responsible for their products even after they are sold. In addition, ensuring sustainable resources, consumption and production patterns is one of the United Nation’s (UN’s) 17 goals to transform our world (UN 2015).

Both the economic aspects and sustainability of PSSs need to pull the continuous design and development of changeable products. Continuous design and development require shifting the concept of the product lifecycle from sequential to cyclical, where the nature of manufacturing changes from production to continuous renovation. Changeable products and PSSs have the potential to extend product lifecycles and support a longer term relationship between suppliers and customers (Richter et al. 2010).

After analysing each of the IRs, the authors conclude that smart design engineering should be capable of dealing with the advantages and challenges according to the trends demonstrated by each perspective:

- *Technology* evolved from automation to autonomy and communication.
- *Production* the increased level of productivity in the factory was pulled by automating from simple and repetitive processes to more elaborate processes, which require autonomous decision making through the access of distributed information.
- *Sales* the customer’s buying decision is not only based on product cost and availability but also on how the product meets his/her individual needs.
- *Marketing* the marketing function evolved to become more accurate and thus provide more timely information about individual customers.
- *Product* over time, product complexity and scope changed so that related services are also considered part of the offered solution as PSSs.
- *Design and development process* the evolution of product complexity and scope and, finally, the opportunity to receive feedback regarding the product during its use indicate a more continuous PDP.
- *Sustainability* the awareness of the factory’s impact in the environment, which was initially related to the factory workers and later to pollution, now encompasses several sustainability aspects, particularly the need for mindful

resource consumption and the creation of circular economies.

3 Methodology of the systematic literature review

The objective of the presented research is to establish the impact of the 4th IR on product design and development and determine the possible features and properties that will shape smart design engineering based on this impact. To achieve this goal, a systematic review of the literature was carried out. The systematic literature review, which is defined as a literature review that follows a strict methodology that enables replicability, was adapted from Biolchini et al. (2005) and consists of three phases: planning, execution and analysis.

3.1 Planning phase

In the planning phase, a search protocol was developed. The authors’ initial approach to this study was to consider the following main question and sub-questions. The sub-questions were defined according to the three production development perspectives used by Morgan and Liker (2006) (process, people and technology/techniques/tools). The indications from the literature regarding the possible benefits, challenges and good practices were also analysed. The leading question, therefore, was as follows:

What are the possible features and properties that will shape (smart) design engineering in the 4th IR?

- How should the composition and knowledge of development teams evolve?
- How should the product design and development process be changed?
- How should the product-development tools, techniques and supporting technologies be adapted?

The purpose of these questions was to guide the search, although the authors were mindful that the literature may not be sufficiently developed to allow all these questions to be comprehensively answered. Hence, the authors did not expect each finding to provide elements to answer the posed questions in depth.

The scope of the review was limited to publications associated with product design and development, which means that the impact of the 4th IR on other lifecycle phases was not considered and that publications that did not include the expression ‘product development’ or ‘design’ were not analysed. The authors chose to include literature covering Industry 4.0, Industrie 4.0, smart industries, and smart products to broaden the search.

Table 1 Search string composition

'product development' OR 'design'	AND	'Industry 4.0' OR 'Industrie 4.0' OR 'smart industry' OR 'smart product'	AND	'cyber-physical' OR 'IoT' OR 'individualisation' OR 'customisation' OR 'sensing' OR 'PSS' OR 'process' OR 'sustainability' OR 'circular'
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Table 2 Summary of the publications selected for further investigation

Year	Total per year	Journal Paper		Conference Paper		Book Chapter		White Paper	
		T	C	T	C	T	C	T	C
1997	1	1	1						
2008	4	3	2	1					
2009	3	2	1	1					
2010	3	3	2						
2011	2	2							
2012	3			2	1	1			
2013	18	3	1	15	3				
2014	24	10	5	13	7	1			
2015	22	7	4	13	2	2			
2016	42	17	8	19	6	5	1	1	1
2017	43	21	10	9	2	13	4		

Particularly, by considering smart products, the literature dated prior to 2011 (when the term Industry 4.0 was coined) could also be analysed. Finally, the literature review queries included terms associated with the perspectives presented in Sect. 2. The definitions of these were chosen according to the following rationales:

- *Technology* 'cyber-physical' systems, since they best define the 4th IR.
- *Production* 'internet of things' when it supports the communication necessary among the cyber-physical systems that form an autonomous (smart) factory.
- *Sales* 'individualisation' or 'customisation', which are pulled by the market.
- *Marketing* 'sensing' when it provides a better understanding of immediate needs.
- *Product* 'product service systems', which encompass the most recent trends.
- *Design and development* since 'design' and 'product development' were also always considered, only the term 'process' was included.
- *Sustainability* the focus was on 'sustainability' or 'circular' economy.

The search string used all possible combinations, as presented in Table 1. Although more terms and synonyms to the actual terms could be added, the authors decided to limit the search to only those presented.

3.2 Execution phase

In the execution phase, the refined search string was initially used to search the Web of Science (WoS) and Scopus databases due to their relevance to the studied research field. To obtain early references to smart products, the search timeframe was not limited. Due to the small number of papers initially found (47 publications), the search was extended to consider the databases available directly from selected publishers' websites: Springer, Elsevier, Taylor and Francis, Institute of Electrical and Electronics Engineers (IEEE), and the American Society of Mechanical Engineers (ASME) digital collection. The publications included in these databases comprised of scientific journals, conference proceedings, books and articles from trade journals. The only restriction posed was that the reviewed articles were in English.

The database search was performed in March 2018. The search string resulted in a total of 778 publications. Some of the references appeared in both databases. To remove duplications, a common list with the titles of the selected publications was generated. The publications' abstracts were read to ensure that the papers were associated product design and development. After applying this exclusion criterion, 118 publications were selected for further investigation.

3.3 Analysis phase

The publications that passed the abstract check were carefully studied, and the findings and associated concepts were extracted. Table 2 organises all the studied publications by year and type (journal paper, conference paper or white paper). The total (t) columns show the total number of selected publications per year, and the cited (C) columns show the number of papers that supported the findings. The table also illustrates the increasing interest in Industry 4.0 design-related aspects after 2013.

During the analysis of the selected papers, each of the papers' paragraphs were labelled according to the sub-questions presented in Sect. 3.1; some paragraphs were related to more than one sub-question. The paragraphs without any relevant information were also marked. The paragraphs with the same labels were then grouped into a single document to allow the authors to identify key findings. The process of identifying the findings consisted of grouping similar comments from different papers that had common goals. Therefore, rather than looking for the repetition of similar words, the authors searched for comments that had the same objective.

Finally, the findings were double-checked by 11 specialists in topics related to the 4th IR. Three specialists were from academia, and eight were from the industry. Moreover, they were based in various countries (Brazil: 3, China: 2, Germany: 1, Kenya: 1, Netherlands: 2, Singapore: 1 and the USA: 1). They analysed the findings according to (1) the impact they perceived each finding to have on the PDDP and (2) the direct relation of the findings to the 4th IR. Therefore, it was possible to determine which findings are characteristic of the 4th IR.

4 Key findings

The previously presented literature review process resulted in the identification of ten key findings that directly impact the design-engineering process of products or PSSs. Of these, six were related to directives or good practices to be considered when performing smart design engineering and were defined as design for excellence (DFX). In the discussion of each finding, the aspects related to people, process and tools and techniques are highlighted. Table 3 lists the findings and the supporting references, which are as follows:

1. Design for empowered users.
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.

4.1 Design for empowered users

Wellsandt and Thoben (2016) show that involving users in activities that are usually in the producer's domain (product creation cycle) is a common business strategy. Indeed, value is defined by and co-created with consumers. Co-creation is essential to mass individualisation, because it enables the consumer to take part in the PDP by expressing his or her requirements/demands or even co-designing the product with a configuration toolkit (Koren et al. 2015). The 4th IR extends the means to involve users and customers as active designers and/or producers. This requires the consideration of the following, as adapted from Srari et al. (2016):

- *Material supply-chain issues* standards (including file formats), compatibility, regulation and certification.
- *User-interface issues* the absence of software, conceptual infrastructure and designer-level knowledge about the production tools' constraints.
- *Organisational issues* the ability of organisations to create and capture value, business-model uncertainty, data-sharing restrictions, governance, ownership and security.

Through open innovation, customers can be empowered to become involved in the front end of the design process using digital design and product development tools and become active members of the product design team, which exceed mass customisation and the possibility of choosing from possible pre-defined alternatives (Würtz et al. 2015). In Würtz et al. (2015), for instance, the customer generates the geometrical dimensions of the product himself/herself, which are produced by assembling a combination of additive manufactured parts and pre-manufactured parts. For example, 247TailorSteel is a company that manufactures customised stainless-steel blanks for several industrial equipment manufacturers in the Netherlands. In this case, an industrial IoT drives a network of manufacturing technologies—or CPSs—that automatically translate customer orders from the upstream online product configurator, through manufacturing planning and control and down to the delivery to the customer (www.247tailorsteel.com).

3D printing is also revolutionising the value chain as the customer himself/herself can produce or forward relevant data streams to capillary distributed services or production laboratories, which are known as distributed manufacturing systems (DMS), in the region that manufactures the product (Rauch et al. 2016).

Table 3 Findings and their supporting references

#	References	Findings									
		1	2	3	4	5	6	7	8	9	10
1	Abramovici et al. (2016)				x						
2	Atzori et al. (2010)		x								
3	Blanco et al. (2017)								x	x	
4	Borgia (2014)		x		x	x					x
5	Broy et al. (2012)		x				x				x
6	Buurman (1997)										
7	Chang et al. (2014)						x				
8	Chang et al. (2017)			x							
9	Damgrave et al. (2013)								x		
10	Dawid et al. (2017)		x		x		x		x	x	
11	Demminger et al. (2016)		x								
12	Duffy et al. (2016)										x
13	Eigner et al. (2013)									x	
14	Eigner et al. (2014)							x	x		
15	Essamlali et al. (2016)			x							
16	Estefan (2008)							x			
17	Gao et al. (2015)		x		x						
18	Gerhard (2017)							x	x		
19	Ghosh et al. (2017)						x				
20	Gubbi et al. (2013)		x								
21	Hehenberger et al. (2016)							x			
22	Hyun Park et al. (2017)										x
23	Iordache (2017)							x			
24	Jiang et al. (2017)				x						
25	Knowles et al. (2015)					x					
26	Koren et al. (2015)	x									
27	Lefèvre et al. (2014)								x		
28	Lehmhus et al. (2016)		x								
29	Lesjak et al. (2016)					x					
30	Luchs et al. (2016)		x								
31	Ma et al. (2017)		x								
32	Monostori et al. (2016)						x				
33	Mehrsai, et al. (2014)			x							
34	Meyer et al. (2009)				x						
35	Morris et al. (2016)								x		
36	Mulder et al. (2015)		x								
37	Ng et al. (2014)						x				
38	Pessôa and Becker (2017)			x							
39	Porter and Heppelmann (2014)				x						
40	Porter and Heppelmann (2015)				x	x					x
41	Rauch et al. (2016)	x									
42	Reiner (2014)					x					
43	Richter et al. (2010)			x							
44	Rodríguez-Mazahua et al. (2016)		x								
45	Rymaszewska et al. (2017)									x	
46	Srai et al. (2016)	x									
47	Stark et al. (2014a)								x		x
48	Stark et al. (2014b)								x		
49	Synnes and Welo (2016)			x							

Table 3 (continued)

#	References	Findings									
		1	2	3	4	5	6	7	8	9	10
50	Tao et al. (2017)				x						
51	Thames and Schaefer (2017)								x		
52	Thoben and Lewandowski (2016)		x		x				x		
53	van Rhijn and Bosch (2017)			x							
54	Wang et al. (2016a)								x		
55	Wellsandt and Thoben (2016)	x								x	
56	Wellsandt et al. (2014)				x				x		
57	Welo et al. (2013)								x		
58	Windelband (2017)		x								
59	Würtz et al. (2015)	x									
60	Xing and Belusko (2008)			x							
61	Xu et al. (2014)		x								
62	Zallio and Berry (2017)			x							
Total number of related articles		5	14	10	12	5	5	5	14	5	6

According to the sub-questions presented in Sect. 3.1, design for empowered users has the following impacts on design engineering:

- *People* having empowered users as part of the development team requires informing and educating them to work with specific user-friendly process and/or tools.
- *Process* the user role must be explicitly defined in the design-engineering process and demonstrate which tasks they are expected to perform in each phase (inputs, pre-conditions, activities, outputs, etc.). Meta-solutions composed by building blocks can facilitate empowered users to create individualised final solutions. These building blocks can be designed to both guarantee that the restrictions imposed by other stakeholders are respected (i.e., regulation) and allow the customer to either produce the product himself/herself or do so using DMSs.
- *Tools, techniques and technologies* Empowerment is only possible through proper design tools (i.e., more flexible product configurators or more user-friendly computer-aided design—CAD software) and a flexible and viable production capacity, such as through 3D printing.

4.2 Design for product-in-use feedback

Learning from product use is of paramount importance for designing successful products; a well-executed user-centred design decreases overall development time and improves product quality (Buurman 1997). The convergence of embedded systems, global networks and business web and interactive CPS service creation by users is bringing a new wave of innovations and changes in human-system cooperation, usability and safety (Broy et al. 2012). It facilitates the access to endusers and improves communication among the

members of the multi-disciplinary design team, particularly during the early process of idea generation. Recent technical developments, such as 3D printing, computer simulation, cyber-physical systems, augmented reality and online mass customisation toolkits have increased the possibilities of assessing consumer response to experiential product attributes in concept optimisation (Luchs et al. 2016). Living labs are one example of the application of these technologies (Mulder et al. 2015), prototypes of which send information through sensors with user consent but without user awareness.

Data showing how the products are used and their actual performance and condition provides insight regarding the infield adequacy according to real-use scenarios, which (1) might result in the identification of opportunities for updating or upgrading the product and (2) would provide an understanding of how customer needs are evolving (Dawid et al. 2017; Rodríguez-Mazahua et al. 2016). These data also allow companies to determine better and more-tailored maintenance strategies (Gao et al. 2015; Windelband 2017). For example, Demminger et al. (2016) present a condition-based maintenance case, where data collected during the life cycle is evaluated to determine the component status and plan its maintenance. In another example, Ma et al. (2017) demonstrate an approach for collecting and transforming product usage data, including product time-dependent performance feature data and field data, into valuable information to guide product design improvement by encouraging design and manufacturing engineers identify design issues and increase product reliability.

Remote monitoring and cloud monitoring are examples that employ IoT techniques for data acquisition and network techniques for data and information interaction (Gao et al. 2015). Future products can be outfitted with sensors that

connect to the cloud, enabling after-sales service offerings. Smartness could be customised by linking additive manufacturing and sensor integration to directly print smart products (Lehmhus et al. 2016). Regarding data provision, aggregated and context-related information has to be integrated seamlessly into engineering tools (Thoben and Lewandowski 2016). Atzori et al. (2010); Gubbi et al. (2013); and Xu et al. (2014) list several IoT applications and possible data to be collected. Borgia (2014) points out some key challenges to IoT adoption and implementation, which include the need for a scalable, flexible, secure and cost-efficient architecture that is able to cope with the complexity of the chosen scenario.

According to the sub-questions presented in Sect. 3.1, the design for product-in-use feedback has the following impacts on design engineering:

- *People* the development team must be aware of and concerned about ethics, privacy and user-data confidentiality issues.
- *Process* preserving knowledge obtained using the customer as an active designer should also be planned; this knowledge is a powerful asset that drives the evolution of offered solutions and long-term value delivery. Design engineering must promote the identification of necessary feedback (what data and why) during the development as well as the use phase. The designer, therefore, will determine the data-gathering procedures and the necessary technologies that will be included in product design (i.e., sensors and the IoT).
- *Tools, techniques and technologies* 3D printing for rapid prototyping and user feedback could be considered during the design process. Including sensing and communicating capabilities in the solution should not be considered an addition; rather, the solution could be designed with integrated sensors and incorporate the IoT to obtain in-use feedback.

4.3 Design for changeability

Changeable products and PSSs are potential solutions to decreased lifecycles and resource scarcity (Richter et al. 2010; Xing and Belusko 2008) and are also ways to deal with obsolescence issues (Zallio and Berry 2017). Van Rhijn and Bosch (2017) conclude that closed-loop systems will increase future customer demand for easy upgrading, which requires a highly modular and operator-friendly product design in addition to early-stage testing and the ability to implement upgrades, while the product is in use anywhere in the world. Mehra et al. (2014) propose the notion of x-gradeability regarding products' lifecycles, which reflects a new design and manufacturing concept called make-to-xgrade (MTX). In MTX, embedded products (or modules)

not only provide connectivity but also facilitate multilateral interactions and the notion of intelligent products with extended functionalities. Furthermore, the vast variety of products and end-of-life uncertainties of used products increase the importance of optimising disassembly in each stage of the product lifecycle to achieve a closed-loop and sustainable product lifecycle (Chang et al. 2017).

In summary, changeable products are those with modules that have built-in robustness against small use variations, are able to adapt to different use experiences and new technologies and can flexibly update and upgrade (Richter et al. 2010). This poses an additional challenge for designers, who need to consider actual and future use scenarios and possible technology evolution, thus requiring them to make decisions regarding the appropriate built-in changeable options (Pessôa and Becker 2017).

Working with options during the development process is not a new approach. Lean product development uses set-based concurrent engineering (SBCE). SBCE advocates keeping a set of design alternatives until the product is finalised to reduce the risk of rework cycles while obtaining more knowledge (Ward et al. 1995). Some examples of SBCE application for designing smart products can be found in Essamlali et al. (2016) and Synnes and Welo (2016). However, these cases as in traditional SBCE, consider multiple alternatives only until the final product is specified. In the case of changeable products, the option for changing should be defined early in the design process and remain an option throughout the product's lifecycle (Pessôa and Becker 2017). In this case, the feedback received from the product (which relates to the second finding) use might trigger these remaining options (Pessôa and Becker 2017). Nevertheless, the addition of product variant throughout the lifecycle poses additional challenges for configuration control.

According to the sub-questions presented in Sect. 3.1, design for changeability has the following impacts on design engineering:

- *People* designers should be able to understand what might drive future changes in the product and then decide on changeable solution architectures. This requires educating designers about design options and determining whether and when these options should be executed during the product's use phase.
- *Process* the process should consider how to (1) determine which options to include in the product, (2) decide whether and when these options should be executed and (3) manage the added variants. Consequently, the personalisation and reconfiguration of products should encompass physical core products that are modular, flexible and reconfigurable along with respective service extensions.
- *Tools, techniques and technologies* it is necessary to support the application of SBCE-like approaches through-

out the product lifecycle. The tools and techniques must encourage engineers to define and compare option scenarios.

4.4 Design for data analytics

One significant change to traditional development is the central role of data analytics. Porter and Heppelmann (2015) emphasize that companies must store and manage product data, external data and enterprise data from customer relationship management systems and other platforms. The vast quantities of data now available enable smart products to monitor, control, optimise and, ultimately, work with complete autonomy (Porter and Heppelmann 2014). Furthermore, due to the fact that smart products are intelligent and can adapt to the environment, it is important to manage the product mechanisms that act autonomously, since the creation of value does not end after the product is sold (Abramovici et al. 2016). This data enables the exploration of how human behaviour can change the design of smart products and services, and more informed and self-aware consumption decisions can be made using feedback data resulting from the analysis of interactions between consumers and their self-generated data (Dawid et al. 2017).

Another example is the use of search engines, recommender systems and e-commerce to exploit the increasing amount of information available for free on the Internet. They provide an alternative to survey-based or direct measurement to acquire opinions and extract knowledge from customers and thus better understand what drives and hinders the purchase of new products (Dawid et al. 2017). Furthermore, they can predict the future importance of product features (Jiang et al. 2017). Finally, while the requirements elicitation task typically marks the beginning of the product lifecycle, the inbound information of the elicitation process originates from several product lifecycle phases (e.g., manufacturing, use, service, recycling and disposal) when product-embedded sensors can retrieve products' use information (Wellsandt et al. 2014).

Therefore, it is necessary to adopt a design process approach that starts with a data provision project and consider what expected output from the data analysis supports and simplifies the tasks executed throughout the solution lifecycle (Thoben and Lewandowski 2016). In this sense, it is necessary to create a closed loop of data between the design and assessment phases throughout the solution lifecycle, particularly to enable information sharing and the management of product-service relations (Monostori et al. 2016). In any case, different types of smart products may require different data-analytics approaches; Meyer et al. (2009) present model of classifying intelligent products according to their intelligence level (information handling, problem notification or decision making), the intelligence location

(at the object or through the network) and its aggregation level (item or container).

A core question concerning the design of smart products is what components of the physical lifecycle should be modelled into of the virtual lifecycle and what data has to be acquired and integrated to obtain additional information in the form a digital twin (Abramovici et al. 2016). This relates to the challenge of managing big data due to its different data properties (Borgia 2014). The digital twin (also referred to in the literature as cyber twin, virtual twin, digital shadow and product avatar) is a digital counterpart by which the product is represented (Tao et al. 2017; Thoben and Lewandowski 2016). The digital twin representation can fulfil a number of roles: (1) it can be used to monitor the current usage conditions on the basis of sensors and other usage-data-acquisition technologies embedded into the core physical product and its components; (2) it can act as an interface for both the consumer and the manufacturer or service provider to monitor, select, define and order different product configurations; and (3) it makes it possible to simulate, monitor, optimise, and verify various activities throughout the product lifecycle.

Effectively dealing with physical product data, virtual product data and connected data that link the physical and virtual product helps prevent the occurrence of information islands between different phases of the product lifecycle, the storing of duplicate data in different lifecycle's phases, and supports the integration of big data analysis into various activities during product design, manufacturing and service (Tao et al. 2017).

According to the sub-questions presented in Sect. 3.1, the design for data analytics has the following impacts on design engineering:

- *People* the design team needs education regarding data modelling and data analytics, including artificial intelligence approaches.
- *Process* the design-engineering process must support the use of Internet-available data and in-use feedback data (see the second finding). This can lead to the elicitation of better requirements, better solution concepts and improved technical solutions. Additionally, a digital twin can be a powerful tool to support product development, but for its capabilities to be used to their full advantage, the product must be designed accordingly.
- *Tools, techniques and technologies* tools and techniques must enable the exploitation of Internet-available data and the design of digital twins.

4.5 Design for cyber security

A major technological component of Industry 4.0 is the Internet of Everything (IoE). The IoE goes beyond the sole vertical integration of top-level management systems with

shop-floor field devices; rather, it tightly integrates value-chain stakeholders across companies in both vertical and horizontal ways (Lesjak et al. 2016). Indeed, CPSs equipped with Internet technology require safety, security, privacy and knowledge protection (Reiner 2014). This means that security must be embedded as a first principle in product design and across the value chain (Borgia 2014; Porter and Hepelmann 2015).

According to Knowles et al. (2015), several standards have been published that attempt to integrate security into the system development lifecycle (SDLC); addressing security in the industrial control-system development lifecycle, however, is still in its initial stages. Although information security and assurance standards do not completely address the security requirements of industrial control systems, they are still used extensively in industrial control-system environments.

Lesjak et al. (2016) explicitly state that comprehensive security management and proactive protection mechanisms are required to systematically design and implement a smart service world. They conduct a case study within the Arrowhead project. In the European-funded Arrowhead project, more than 70 partners from across Europe strived to improve the flexibility and efficiency of production at the global scale by means of collaborative automation. As a result, the three most important security challenges identified were transparency, end-to-end data protection and the segregation of data among different stakeholders.

According to the sub-questions presented in Sect. 3.1, design for cyber security has the following impacts on design engineering:

- *People* this finding also addresses the need for a design team educated regarding IT-related topics to understand the advantages and vulnerabilities (cyber threats) of adding software and the IoT to designed solutions in addition to the possible counter measures that must be integrated into the design.
- *Process* the communication among the systems and the use of the Internet bring the challenges of the cyber world to the physical world. Design engineering should, therefore, guarantee the consideration of threats such as viruses and hackers. Consequently, designers should also guarantee data security.
- *Tools, techniques and technologies* there must be tools and techniques to model and test cyber-secure smart systems.

4.6 Design for emotional interaction

As observed by Dawid et al. (2017), although most smart products are currently isolated solutions, the fragmentation that can occur when a larger number of products co-exist in

an environment without truly cooperating indicates missed opportunities and challenges for exploiting synergies. This, however, demands that smart products become aware of which other smart products are available in their vicinity and that they have a common language and established standards for interacting. The largest challenge for smart products is, however, to bridge the interface gap between, on the one hand, the technology that becomes ever more invisible and, on the other hand, the user who is less and less aware of what smart appliances they might be using, what information these appliances collect (and with whom they share this information) and how they can be controlled, configured, taught, and used (Dawid et al. 2017).

An interesting phenomenon is the emergence of emotional bonds between user and product, which are potentially stronger the more interactive and ‘intelligent’ the device is. Chang et al. (2014) study the influence of different product characteristics on consumer purchase intention, and they find that connectivity, interactivity, telepresence, intelligence, convenience and security all positively influenced purchase intention via functional experience. This requires a deeper understanding of user, task and emotional requirements. Ng et al. (2014) explore how human behaviour can change the design of smart products and services and how interactions between consumers and their self-generated data can be analysed and fed back to support more informed and self-aware consumption decisions.

Dawid et al. (2017) analyse some psychological aspects related to the interaction between humans and smart products and identify two possible scenarios: (1) having humans directly interface with smart products that communicate and cooperate among themselves, and (2) cognitive humanoid robots will evolve as flexible assistants in our houses and cities instead of distributing the smartness into installed components. They argue that the latter alternative is more natural and is easier for users control, thus reducing the need for embedding smartness into several devices, facilitating the designer to deal with questions of privacy, reducing the device’s interaction complexity, and serving as a gateway to control and report the status of smart home products.

Ghosh et al. (2017) propose a cyber-emphatic design framework that considers data feedback from product-embedded sensors, which is processed through a network of psychological constructs. As a result, they identify the potential to manipulate product features and then measure the changes in perception using sensors and psychological construct models.

Solving these social challenges implies new engineering strategies, which call for the participatory analysis and design of systems and services that are (1) manageable, tailorable, trustworthy, fault-tolerant and accountable; (2) capable of learning from users’ behaviours; (3) self-determined and controllable by the users and (4) compatible

with non-networked systems and services as well as drop-outs (Broy et al. 2012). For this vision to become reality, significant steps still need to be taken in terms of cognitive interaction technology, which is the research field that investigates how technical systems can deeply understand what they perceive, how to robustly manipulate physical objects and how to communicate with human users to provide assistance (Dawid et al. 2017).

With the addition of communication capabilities, the new products might not act alone but could communicate and coordinate action with other smart products. Consequently, new failure modes could arise from this interaction. A metaphor that can be made is that of parents educating their child and making sure they behave accordingly regardless of whatever situation may arise. This finding also determines that the solution should be designed not only to provide functionality but to create the appropriate emotional response. To enforce these emotional bounds, the product should evolve according to its relationship with the user.

According to the sub-questions presented in Sect. 3.1, design for emotional interaction has the following impacts on design engineering:

- *People* to design the appropriate human–machine interaction, the design team should master the social as well as the technical sciences. Ethical and privacy aspects and regulations should also be taken into consideration.
- *Process* new failure modes could arise from this interaction and must be analysed during the design. Special attention should be paid to machine learning to ensuring that products behave accordingly regardless of whatever situation may arise. This finding also determines that the solution should be designed not only to provide functionality but also to create the appropriate emotional response. To enforce these emotional bounds, the product should be designed to evolve according to its relationship with the user.
- *Tools, techniques and technologies* the design tools and techniques should support the modelling and testing of both planned and unplanned interaction scenarios.

4.7 Continuous engineering supported by MBSE

Continuous engineering builds on the foundation of systems-engineering practices by persistently applying engineering tools, methods and techniques to address change and close gaps between current design plans and final requirements (Iordache 2017). This requires new product design processes that integrate design methods in which the designers consider all engineering disciplines simultaneously, thus hindering a mutual understanding in communication through documented interactions and interfaces between the various

disciplines in addition to operational issues, such as privacy (Hehenberger et al. 2016).

To cope with this complexity, information traceability throughout the entire system lifecycle is required. The use of models instead of documents, where a discipline-neutral view of the system specification is created, supports this traceability (Eigner et al. 2014). Regarding this, a shift from separate designs for physical systems, control subsystems and software architecture to an integrated and optimised design can be observed in the field of systems engineering (Gerhard 2017), one approach of which is MBSE. MBSE emphasises applying rigorous visual modelling principles and best practices to systems-engineering activities throughout the SDLC. These systems-engineering activities include but are not limited to requirements analysis, validation and verification; functional analysis and allocations; performance analysis and trade studies; and system architecture specification (Estefan 2008). The resulting coherent system model facilitates the understanding and overview of the complexity of the developed system and simplifies the communication in a multi-disciplinary development team (Eigner et al. 2014).

According to the sub-sections presented in Sect. 3.1, continuous engineering supported by MBSE has the following impacts on design engineering:

- *People* necessary education regarding systems engineering, particularly in model-based approaches, such as MBSE.
- *Process* the product should be modelled on a foundation composed of the solution's requirements, data, material and electrical flows; the MBSE is an interesting potential approach to this in that it helps guarantee the alignment and integration of all the disciplines through the solution's design and development.
- *Tools, techniques and technologies* MBSE and MBSE-capable tools.

4.8 System lifecycle management

There is a pressing need to align information technology (IT) and products' lifecycle management processes through models that support effective decision making (Morris et al. 2016). Product-embedded sensors, when operational in the field, work as permanent test rigs and share product-captured data throughout its lifecycle (Thoben and Lewandowski 2016; Wellsandt et al. 2014). This sensor-based round-the-clock collection of data by smart products enables data-driven improvements of follow product relaunchees on the basis of existing usage or behaviour patterns (Dawid et al. 2017).

Thames and Schaefer (2017) foresaw that computer-aided product development would become predominantly

cloud-based through a type of parallel and distributed system consisting of a collection of inter-connected physical and virtualised service pools of design and manufacturing resources (e.g., parts, assemblies, and CAD/CAM tools) as well as intelligent search capabilities for design and manufacturing solutions. This potentially enables customers, engineers and other participants to share information through social media by integrating web tools into product-design processes through a product realisation model of open innovation and rapid product development with minimum costs (Wang et al. 2016b).

Product Lifecycle Management (PLM) systems, therefore, should be able to manage complex product configurations, including electronics and software, and also depict changes in the configuration during operation (Morris et al. 2016). It is essential that PLM solutions are dynamically adaptable and reflect the constantly changing data models along with the process changes in the organisations (Eigner et al. 2014; Gerhard 2017). Indeed, the exchange and integration of CAD/CAE models within the product lifecycle management context is one of the major concerns for many companies, especially in mechatronic engineering (Lefèvre et al. 2014). This scenario requires ontologies for semantic data integration that define a mediated schema that specifies possible relations between heterogeneous data formats (Stark et al. 2014a). It is essential to provide software solutions that enable the management of these neutral file formats and data through a collaborative simulation lifecycle management platform (Lefèvre et al. 2014).

According to Stark et al. (2014b) one limitation of today's PLM solutions is the lack of intelligence to relieve engineers from some of the rather mundane data-management-centric activities, which become more complex due to the sheer amount of data now available and which also poses a challenge for maintaining systems-engineering traceability. They foresaw the evolution of intelligence in PLM solutions to support semi-automated data integration and decision support (artificial intelligence in PLM) up to the full automation of routine engineering activities, information linkage and multi-criteria decision support.

For example, Stark et al. (2014a) present the iProd project from Fraunhofer IPK, in which ontologies specifying a high-level engineering metamodel were developed to interlink different engineering artefacts that are generated and used in the PDP. These ontologies re-use many concepts of SysML and STEP 233 and were designed to be easily adaptable for different engineering domains. When adapted to the specific vocabulary of one company, an additional ontology-based data integration framework allows for the specification of interfaces for different PLM solutions. Through these interfaces, existing engineering data can be linked and subsequently processed by reasoning algorithms.

Simple and visual communication methods, such as those from lean product-development visual management, have proven to be powerful tools to keep the development teams of Norwegian manufacturing companies synchronised (Welo et al. 2013). Composing a synthetic environment (SE) with the use of virtual reality (V-R) tools also enables developers to communicate and visualise their problems and solutions and facilitates diverse multi-stakeholder collaboration and decision-making processes (Damgrave et al. 2013).

However, new technology is not enough. New technology literacy results in additional benefits, where a shared understanding between engineering and design/marketing leads to better design teams performance. This literacy is reflected in the quality of the developed projects, enhances the innovation and technological quality of the products and considerably reduces error rates and technological unfeasibility issues (Blanco et al. 2017).

According to the sub-questions presented in Sect. 3.1, system lifecycle management has the following impacts on design engineering:

- *People* the development team needs both engineering and market literacy.
- *Process* design engineering should foster collaboration among engineering disciplines and within the value chain. The use of visual communication also facilitates collaboration and information sharing.
- *Tools, techniques and technologies* PLM and CAD/CAM tools 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).

4.9 Increased stakeholder quantity and complexity

According to Dawid et al. (2017), consumers' perceptions of various smart features, such as autonomy, human-like interaction, the ability to cooperate, reactivity, adaptability and multi-functionality, may play a role in stakeholder quantity and complexity. Consumers' attitudes, consumption values and intended behavioural usage regarding smart products need to be investigated more closely to determine whether smart(er) products are really better. This requires reshaping the product concept using all involved processes and considering the product's lifecycle (Eigner et al. 2013).

Modelling smart products requires interdisciplinary and transdisciplinary collaboration among several intermediary stakeholders in addition to producers and customers, including empowered ones (Blanco et al. 2017; Wellsandt and Thoben 2016), such as (1) managers responsible for introducing smart products to the market to consider the market perspective, (2) experts from the underlying technical fields to learn about the specifics of the alternative systems and

to understand their potential pros and cons, (3) sociologists and psychologists to help overcome mental or other barriers during the adoption process, (4) lawyers (in some cases) to address any legal concerns, since smart products often raise data protection issues and/or liability issues, (5) representatives from each group of prospective users of these products, (6) policy makers and their specific interests (e.g., concerning the limitation of energy and/or resource consumption, which may be actuated by subsidies and/or enforced by regulations) (Dawid et al. 2017).

Rymaszewska et al. (2017) demonstrate three cases of business-to-business (B2B) IoT powered servitisation, in which the implementation of strategic issues relates to several different areas and different stakeholders outside the technical field. Failing to take into account these scenarios would jeopardise the developed solution.

According to the sub-questions presented in Sect. 3.1, increased stakeholder quantity and complexity has the following impacts on design engineering:

- *People* the need for systems thinking to broadly identify possible stakeholders.
- *Process* identifying the value the solution should deliver goes beyond understanding the customer's expectations. Stakeholders throughout the solution lifecycle must be identified, and scenarios must be created to estimate how their needs might evolve over time. This allows for the development of flexible, resilient, enduring and sustainable solutions.
- *Tools, techniques and technologies* techniques that capture the voices of both customers and stakeholders. These tools should also allow for the creation of scenarios that support the balance of these needs.

4.10 Changes in quality perception

Hyun Park et al. (2017) argue that the concept of quality was broadened by the 4th IR due to mass customisation and personalised production. They mention that design, safety and personalised service quality are becoming more important and that intelligent manufacturing, robotisation, and 3D printing are commoditising manufacturing quality. This requires expanded quality modelling and engineering standards with (1) models for in-use quality, quality of service, compliance, technical and organisational models and methods for quality assurance and (2) the elicitation and negotiation of acceptance requirements and corresponding system concepts (e.g., governance and fairness) (Broy et al. 2012). Another aspect to be considered is the concern regarding privacy and data security (Borgia 2014; Porter and Heppelmann 2015).

After identifying customers' demands, quick production is perhaps the most important factor that will enable a

company to satisfy customers and survive (Hyun Park et al. 2017). More broadly, introducing the concept of smart products throughout the manufacturing value chain and reaping the related benefits will improve product quality through the integration of 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. Fast IT equipped with efficient inspection tools enable the automatic identification of defective products and automatic line-stop production systems (Stark et al. 2014a).

This finding states that quality perception is becoming more dependent on personalised goals and experiences than on aspects generally accepted by the target market. In addition, the offering of individual solutions might require individualised approaches for lifecycle-long quality control and assurance.

According to the sub-questions presented in Sect. 3.1, changes in quality perception have the following impacts on design engineering:

- *People* this finding shows that customers' expectations are also evolving during the 4th IR and that they expect to benefit from new technologies throughout the solution lifecycle. The development team thus needs to adopt a more holistic view of the quality delivered through the solutions lifecycle.
- *Process* this finding reinforces what has been articulated in the previous findings. To close the information loop between the product and the manufacturing company and receive positive feedback (quality perception) from the customers, the product should be designed to fully benefit from 4th IR technologies.
- *Tools, techniques and technologies* Techniques that support the understanding of how customer expectations might evolve throughout the solution lifecycle.

5 Discussion of findings

The previous findings show recurrent topics identified in the reviewed literature. Although they are part of the recent product design and development discussion and, therefore, within the 4th IR period, to determine how they shape smart design engineering, it is necessary to determine (1) the strength of their connection to the 4th IR and (2) the extent of the required changes to the PDDP order to implement said findings. A group of 11 experts was invited to evaluate the findings according to these two criteria. Of these experts, eight were from academia, and three were from the industry. Moreover, they were from various countries (Brazil: 3, China: 2, Germany: 1, Kenya: 1, the Netherlands: 2, Singapore: 1 and the USA: 1). Figure 2 presents the distribution

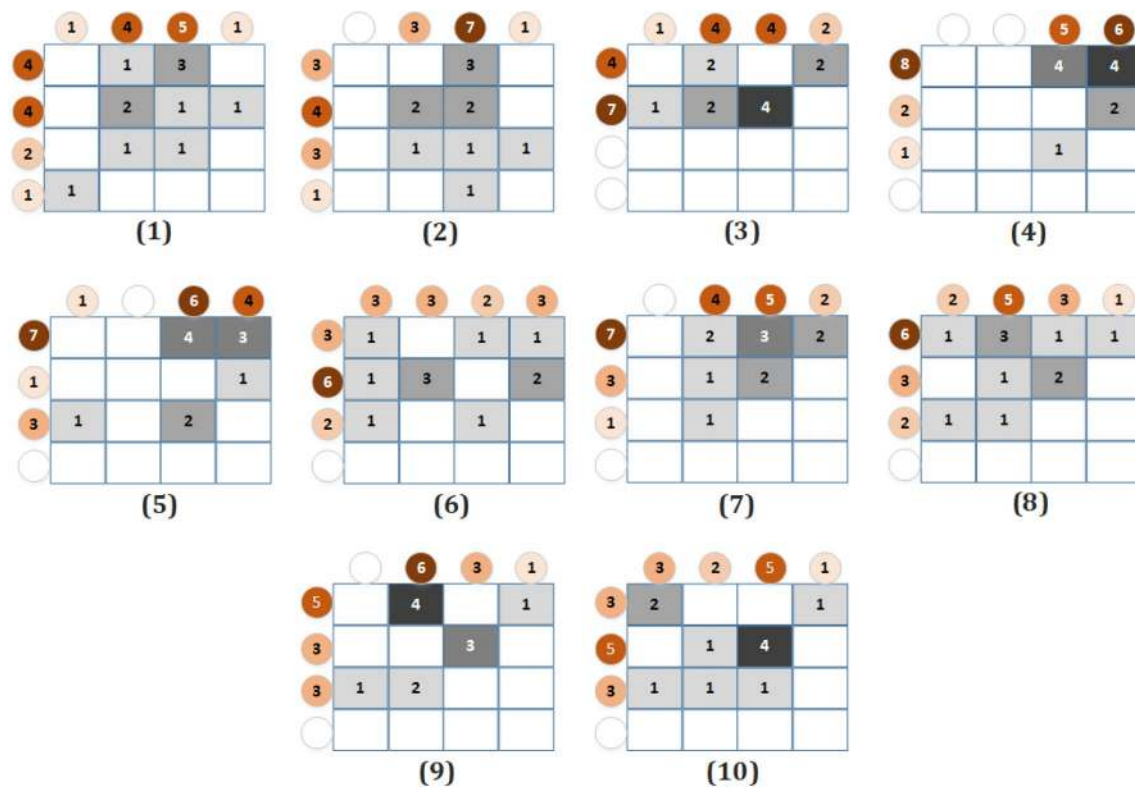
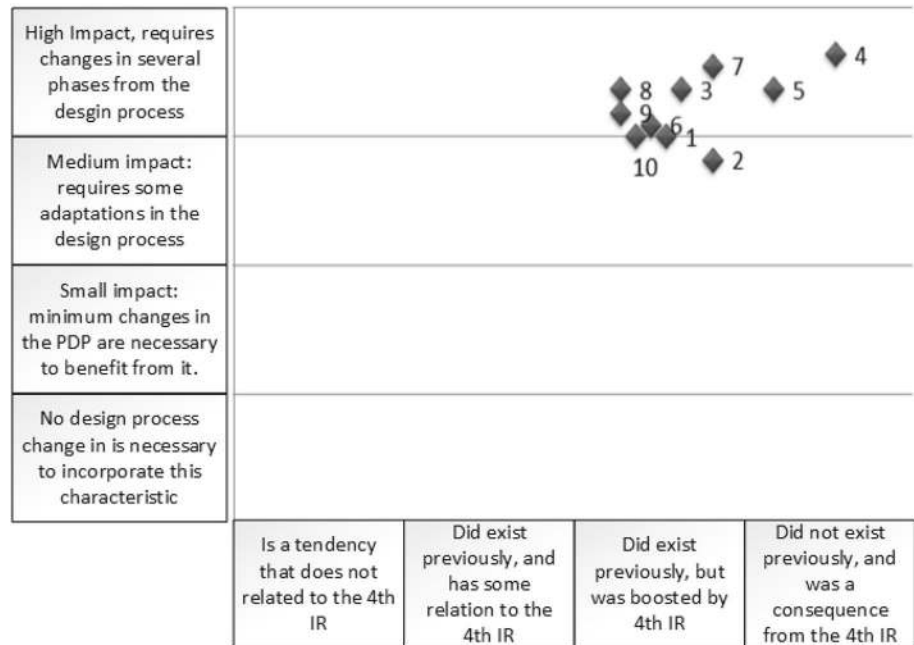


Fig. 2 How the experts rated each finding

Fig. 3 Final positioning of the findings



of the individual evaluations for each finding, which determined the final positioning of the findings according to the criteria (Fig. 3).

The final findings' positions were determined by calculating the mean of the histograms from Fig. 2, which indicated the following:

- Findings 4 and 5 are important consequences of the 4th IR and also require relevant design engineering changes to be fully implemented.
- The remaining findings were all somehow advanced by the 4th IR.
- Findings 4 and 7 were considered to have more impact in the PDDP.
- All findings have either high or medium impacts on PDD, which corroborates their importance in the research agenda for PDDP improvement.

Regarding the sub-questions presented in Sect. 3.1, this work aims to determine the features and properties that will shape smart design engineering throughout the 4th IR in terms of people; process; and tools, techniques and technologies. The presented results indicate that findings 2, 4, 5 and 7 are the most relevant for defining how smart design engineering will be shaped:

- *People* to take full advantage of opportunities presented by the 4th IR, the design and development team must be educated in IT-related subjects, particularly in data modelling, data analytics (including artificial intelligence approaches), the IoT and cyber security. Knowledge of systems engineering and particularly model-based approaches such as MBSE, will facilitate the understanding and synchronisation of several disciplines involved in design and development. Finally, each team member must be aware of and concerned about ethics, privacy and user-data confidentiality issues.
- *Process* the development process must be improved to facilitate the use of the already available data (Internet-available data and in-use feedback data) to design solutions capable of gathering data to be used in future design cycles. When designing a solution, its possible digital twins should also be considered by determining which feedback is useful (what data and why) during the development and the use phases. This will allow the data-gathering procedures to be used and the supporting technologies to be placed (i.e., sensors and the IoT). The development process should also guarantee the solution's cyber security. Finally, the solution should be modelled to guarantee the alignment and integration of all the disciplines through its design and development, of which MBSE is a strong candidate approach.
- *Tools, techniques and technologies* tools for exploiting Internet-available data, IT design tools, techniques for designing digital twins and tools and techniques to model and test cyber-secure smart systems. Technologies such as rapid prototyping using 3D printing could be considered during design in addition to added sensors and the use of the IoT to obtain in-use feedback. Finally, MBSE and MBSE-capable tools must be used.

6 Final remarks

This work's objective was to provide an understanding of the impact of the 4th IR on the engineering design process, which is shaping the PDDP of smart design engineering.

The initial review of the literature regarding each of the IRs identified seven relevant perspectives: technology, production, sales, marketing, product, design and development process, and environment. Rather than trying to provide a final study on how the IRs changed the industrial landscape, these perspectives provided guideline and keywords for our literature review on the 4th IR. After 778 studies were initially found, 118 references were selected for detailed analysis, which revealed an increasing number of papers related to the 4th IR from 2013 onwards. Of these publications, 62 supported the ten findings presented in the paper:

1. Design for empowered users.
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.

The further analysis of these findings by 11 specialists of topics related to the 4th IR have shown that findings 2, 4, 5 and 7 are the most characteristic of the 4th IR and, therefore, have more influence on shaping smart design engineering. These three findings indicate the following:

- The design-engineering team must be educated in IT-related subjects, particularly in data modelling, data analytics (including artificial intelligence approaches), the IoT and cyber security. Knowledge of systems engineering and particularly model-based approaches such as MBSE, will support the understanding and synchronisation of several disciplines involved in design and development. Finally, each team member must be aware and concerned about ethics, privacy and user-data confidentiality issues.
- The design-engineering process must support the use of Internet-available data and in-use feedback data. Digital twins can be a powerful tool to support product development, but it requires that the product be designed to take full advantage of its capabilities. The parallel design of a solution and its possible digital twins help determine the procedures that must be

implemented and technologies that must be placed (i.e., sensors and the IoT). To create solutions that fully benefit from the IoT, the development process should guarantee security against cyber threats. Finally, MBSE is an interesting candidate approach. It helps the traceability and integration of all the disciplines through the solution's design and development.

- Design engineering must be supported by tools, techniques and technologies that allow for the exploitation of Internet-available data, the integration of hardware and software design (MBSE-capable tools), support the creation of digital twins, model and test cyber-secure smart systems, permit rapid prototyping using 3D printing and help define the use of sensors and the IoT.

Despite its contributions, this study has some limitations, particularly because it focuses on a recent and under-developed topic. The increasing number of publications on the subject can support further analyses regarding how the findings interact with one another; these are the challenges and possible approaches to effectively implement smart design engineering. Although the findings were evaluated by specialists from different countries and from both academia and the industry, further studies that gather additional feedback about the findings are necessary. Finally, the findings demonstrate opportunities for further research as they indicate the need for further education, an improved process and new tools and techniques.

In conclusion, this literature review fills the initially identified gap by providing a preliminary understanding of the 4th IR's impact on PDD. Furthermore, the ten presented findings give a general representation of the subject that can support both researchers and practitioners in their own applications.

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