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Design Engineering in the Age of Industry 4.0

Industry 4.0 is based on the digitization of manufacturing industries and has raised the prospect for substantial improvements in productivity, quality, and customer satisfaction. This digital transformation not only affects the way products are manufactured but also creates new opportunities for the design of products, processes, services, and systems. Unlike traditional design practices based on system-centric concepts, design for these new opportunities requires a holistic view of the human (stakeholder), artefact (product), and process (realization) dimensions of the design problem. In this paper we envision a "human-cyber-physical view of the systems realization ecosystem," termed "Design Engineering 4.0 (DE4.0)," to reconceptualize how cyber and physical technologies can be seamlessly integrated to identify and fulfil customer needs and garner the benefits of Industry 4.0. In this paper, we review the evolution of Engineering Design in response to advances in several strategic areas including smart and connected products, end-to-end digital integration, customization and personalization, data-driven design, digital twins and intelligent design automation, extended supply chains and agile collaboration networks, open innovation, co-creation and crowdsourcing, product servitization and anything-as-a-service, and platformization for the sharing economy. We postulate that DE 4.0 will account for drivers such as Internet of Things, Internet of People, Internet of Services, and Internet of Commerce to deliver on the promise of Industry 4.0 effectively and efficiently. Further, we identify key issues to be addressed in DE 4.0 and engage the design research community on the challenges that the future holds. [DOI: 10.1115/1.4051041]

Keywords: Industry 4.0, industrial IoT, human-cyber-physical systems, smart manufacturing, operations and services, smart and connected products, design engineering 4.0, design automation, design for manufacturing, design integration, design methodology

1 Frame of Reference[2]

Integration of smart sensors and networked manufacturing systems has given rise to human-cyber-physical manufacturing systems that can address the requirements of individual customers on a global scale [1–8]. The ability to bring together technologies such as Internet of Things (IoT), Big Data Analysis, Machine Intelligence with traditional technologies such as Smart Automation, Supply Chain, Logistics, and Cloud Computing has resulted in a new wave of advances in manufacturing technologies for product realization [9], which are collectively envisioned as Industry 4.0 [10]. Factories conforming to Industry 4.0 will integrate services across the entire manufacturing and operations processes and will be able to adapt to disruptions in real-time, thereby improving the quality of products and services [11]. The vertical integration of IoT and data analytics will enable these factories to optimize supply and logistic networks, implement policies based on predictive instead of reactive behaviors, improve end-to-end throughputs, and provide services and products at a lower cost [12].

Industry 4.0 represents the Fourth Industrial Revolution and provides a framework to address the challenges arising in the integration of cyber systems and physical resources and covers all aspects of manufacturing systems [13], including robust and flexible automation; data collection, analysis, learning and decision-making; distributed production systems; industrial IoT; and supply chain integration. Industry 4.0 is characterized by a digital model of end-to-end supply chain enabled by smart manufacturing processes, and thus provides a mechanism to transfer autonomy from the physical realm to the cyber-physical realm. Cyber representation of physical processes is much more involved than just networking the associated components of the manufacturing system and involves human interaction with the automation, leading to a human-cyber-physical system [14]. Systems realization in the age of Industry 4.0 requires a new paradigm that considers the distributed and networked aspect of the manufacturing processes [15]. The design process must be able to satisfy the structural

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[2] Definitions of the terms used are in the Appendix–Glossary.

Contributed by the Design Engineering Division of ASME for publication in the JOURNAL OF MECHANICAL DESIGN. Manuscript received April 8, 2021; final manuscript received April 28, 2021; published online June 4, 2021. Assoc. Editor: Wei Chen.

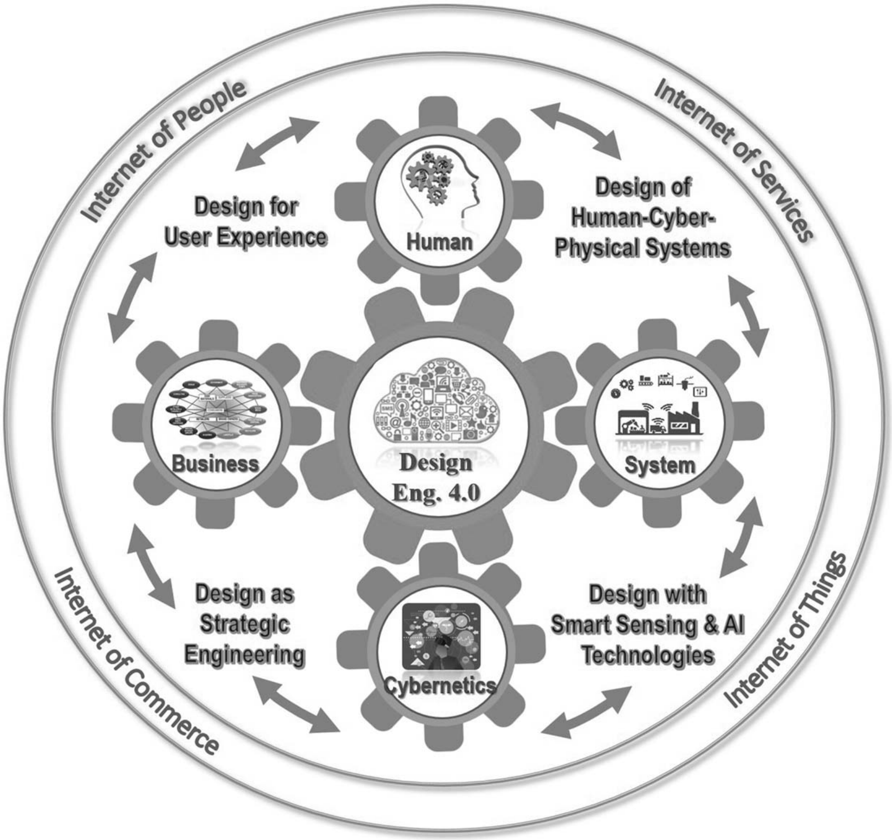

Fig. 1 Design Engineering 4.0: Human-cyber-physical View of the Systems Realization Ecosystem

requirements and constraints on the design and enable the validation of the overall performance. The process must be theoretically sound and should also enable the use of empirical data to validate the models and the performance [16].

The digital transformation of manufacturing industries brought about by Industry 4.0 has created a framework through which substantial improvements in productivity, quality, and customer satisfaction can be achieved. This digital transformation not only affects the way products are manufactured but also creates new opportunities for the design of products, processes, services, and systems. Earlier attempts at implementing Industry 4.0 involved traditional design practices based on system-centric concepts and siloed-designs and focused on enabling interactions between humans and cyber-physical systems, integration of smart sensing and AI technologies, improvement of user experience (UX), and strategic engineering for product creation. However, such approaches are lacking as these new opportunities require designers to take into account user preferences and how users like to interact with the products and between themselves (Internet of People); how businesses can monetize services (Internet of Commerce); how to customize products and services to user requirements while producing products of “zero lot size” and “mass production costs” (Internet of Services); and how to design systems that can collaborate and adapt to improve product quality, process reliability, system agility, and sustainability of the systems realization ecosystem (Internet of Things). Therefore, Design Engineering of the future, that is, Design Engineering 4.0 (DE4.0), must embody a “human-cyber-physical view of the systems realization ecosystem” and reconceptualize how cyber and physical technologies can be seamlessly integrated to identify and fulfil customer needs and garner the benefits of Industry 4.0. The embodiment of human-cyber-physical view of the systems realization ecosystem represented by DE4.0 is shown in Fig. 1.

In this paper, we review the evolution of Engineering Design to DE4.0 in response to advances in several strategic areas and lay out the prospects for systems realization in the age of Industry 4.0. A vision of DE4.0 is outlined in Sec. 2 in accordance with four perspectives, including human, system, cybernetics, and business. In Sec. 3, we present the key principles of Industry 4.0 and discuss emerging issues and opportunities in several strategic areas. In Sec. 4, future directions and outlooks for DE 4.0 are discussed from the human, business, systems, and cybernetics perspectives. Our view on the prospects and challenges for the DE4.0 community are then presented in Sec. 5.

2 Anatomy of Design Engineering 4.0 in the Context of Industry 4.0

Industry 4.0 has transformed manufacturing industries into a new paradigm of smart, cyberized, and sustainable production and operations, making possible substantial improvements in productivity, quality, and customer satisfaction of products, processes, and services [17]. The expected technological advances facilitate revolutionary changes that can bring about significant impacts on many industrial sectors. Industry 4.0 has profound implications on many aspects of our society, such as Electric Utility 4.0 [18], Healthcare 4.0 [19,20], Dentistry 4.0 [21], Service 4.0 [22], Agriculture 4.0 [23,24], Supply Chain 4.0 [25], Materials 4.0 [26], Construction 4.0 [27], and Logistics 4.0 [28,29], to name but a few.

The digital innovations of the Fourth Industrial Revolution not only affect the way factories produce but also invest in the design and engineering techniques of products. The Industry 4.0 principles we elaborate on in Sec. 3 allow for significant improvements in product design thanks to the integration of software components (e.g., sensors, GPS) that are connected to machinery or other physical objects, and make it possible to collect data from the field. The integration of sensor-enabled products into the IoT enables new

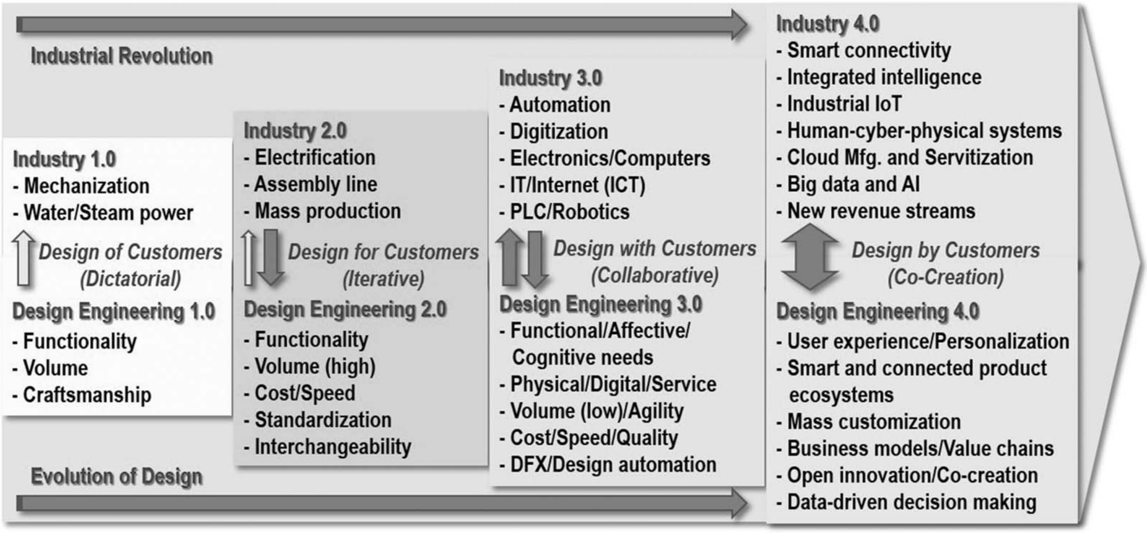

Fig. 2 Design Engineering 4.0 in Line with Industry 4.0

opportunities at every stage of the product life cycle, including their design process itself. Access to data and information generated during the use of a product enables designers to constantly monitor product performance and the way the product is being used. For the potential benefits of smart manufacturing to be realized, the adoption of Industry 4.0 principles must therefore be accompanied by the implementation of management systems through redesign of product realization that makes it possible to store, share and use data collected in the field and ensure proper management of information throughout the product life cycle.

A vision and outline of the new era of DE4.0 including its basic dimensions is provided in Secs. 2.1–2.3.

2.1 Envisioning Design Engineering 4.0.

Motivated by the trend of smart factories of the future toward Industry 4.0, DE4.0 is envisioned to make it possible to better leverage capabilities and resources in a human-cyber-physical production environment. Product realization through strategic engineering of product creation suggests itself to be of primary importance for companies to gain competitive edges [30,31]. Product design must address individual customer needs along with diverse market niches, while maintaining low costs and near mass production efficiency [32,33]. Build-to-order and reconfiguration have become common norms. The traditional spectrum of product fulfillment therefore must be expanded to encompass marketing, design, production, as well as the supply and value chains, which must be aligned with the self-adaptability of a learning organization [34]. The DE4.0 horizon is shifted from a physical product perspective to a total life cycle experience [35]. Design should be more than just dealing with pieces of hardware, but rather should be enacted as co-design of the product and its realization in the context of an entire smart factory ecosystem, including fulfillment, services, user experience, and human satisfaction at both the individual and the community levels, which are fulfilled coherently in a smart and connected manner [36].

The evolution of Engineering Design and its interplay with the industrial processes of manufacturing is shown in Fig. 2. In the early years represented by Industry 1.0, industries attempted to leverage hydraulic and steam power with the emphasis being on offloading labor-intensive manufacturing processes. Design and manufacturing in this era mimicked the process adopted by a human operator. Over time, electrification and assembly lines made possible the mass production of products. These developments in Industry 2.0 meant that products could now be designed to have greater functionality. As a result, Design Engineering 2.0 took into consideration the advances in Industry 2.0 to design products that could be produced in large volumes and at higher rates. The focus of design engineers shifted to product assembly and this led to the push for standardization and interchangeability of parts/processes to harvest the economy of scale. In some cases, redesign was performed to address issues in manufacturing. Industry 3.0 is characterized by increasing automation and the use of CNC machines. Designs were digitized, the manufacturing processes were networked, and data were shared across processes to ensure high-quality products with tight tolerances. The advent on CAD and automation of design processes meant that design could be validated using simulation models to verify manufacturability and to optimize designs. In this period represented by Design Engineering 3.0, design and manufacturing became an iterative process that was more tightly coupled than ever before. For example, CAD designs were used directly in the manufacturing process using CNC Machines. Assembly processes were dictated at the manufacturing end and design considered the need of manufacturing/assembly.

Industry 4.0 looks at networked manufacturing systems that can add product personalization to a mass-produced product. This means that design engineers must now partition base functionality of the product from customizable features, while achieving economics of scale and scope through make-to-order production. The digital transformation of Industry 4.0 is seeding the new economics of DE4.0, which enables product realization to convert the benefits of digital and smart manufacturing into revenue and profit. DE4.0 opens up opportunities for new revenue streams and empowers product development to be agile, responsive, cost–effective, and fast to markets. Engineering Design is evolving to a new paradigm for design by customers through co-creation of product value chain fulfillment in a human-cyber-physical environment [32]. The main characteristics of DE4.0 include user experience and personalization, smart and connected product ecosystems, mass customization [37], focus on business models and value chains, open innovation and co-creation, and data-driven decision-making.

As the technology advances, Design Engineering will continue to evolve and become integral to the design of all systems and not just the manufacturing systems. Systems in the future will incorporate traits of cyber, physical, and social networks, be distributed across geographical domains, have a much wider presence in the cloud, and have no discernible boundaries between their physical and virtual implementations. These systems will have to interact with human users as well as services in a seamless manner. This interaction, which is a defining characteristic of entities in Smart X, is one of the main drivers of design methods that attempt to

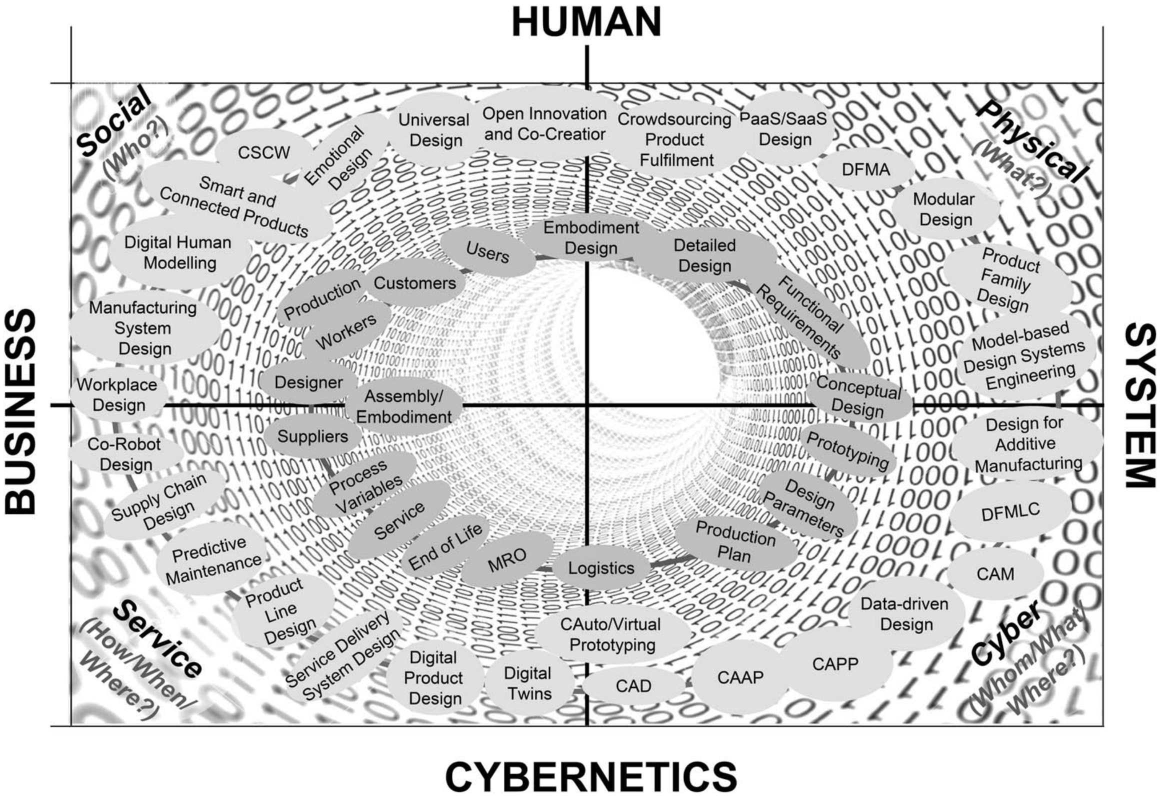

Fig. 3 Design Engineering 4.0—Perspectives and Enablers

deliver on the promise of Industry 4.0. The requirements for these systems stem from the advances of Industry 4.0 and the design of these systems will be the next frontier in engineering design. We envision a universe of DE4.0, as shown in Fig. 3.

2.2 Design Engineering 4.0 Dimensions, Perspectives, and Enablers. Engineering Design involves executing a product design and development process step-by-step through creating and iterating products that solve specific users' problems or address specific needs in a given market. It is generally understood as a three-dimensional space comprising human (stakeholder), artefact (product), and process (realization). However, *DE4.0 goes beyond the three-dimensional space of conventional engineering design to a human-cyber-physical view of the systems realization ecosystem. This ecosystem can be visualized through four different perspectives, namely, human, system, cybernetics, and business,* as shown in Fig. 3. In the inner circle, representative design issues are presented. In the outer circle, state-of-the-art enablers of engineering design are presented, see Fig. 3. However, dimensions and enablers are not mutually exclusive to each of the perspectives.

For example, at the intersection of human-business perspective and business-cybernetics perspective, as the human dimension of design corresponds to different groups of stakeholders involved in the product design and development process from customers or end-users who posit market needs and usability requirements, through designers who account for design decisions, and through manufacturers, workers, and suppliers who commit in the product fulfilment process, which span over the social and service quadrants in Fig. 3. At the intersection of human-system perspective and system-cybernetics perspective, the design process dimension coincides with a timeline of various design tasks and resources that are organized as design projects and enacted throughout a product realization life cycle, from requirement analysis to prototyping, production, logistics, and end-of-life where enablers vary from CAD, CAM, DFMA, DFMLC, and so on, see quadrant cyber-physical in Fig. 3. At the intersection of the system-cybernetics perspective and cybernetic-business perspective, the product dimension refers to specific contents of the product at different stages of the design process, including requirement information, decision variables regarding design and manufacturing, physical or digital form of the product, CAD/CAE models and assembly drawings, production and service operations plans, and so on (see the cyber-service quadrant in Fig. 3). These are some examples of diverse design topics that are placed in the DE 4.0 universe, as presented in Fig. 3. This characterization of design helps articulate multiple facets and the broader scope of design problem solving. For any design research topic, the four basic questions could be "Who/Whom," "What," "Where," "How," and When" along the respective human, system, cybernetics, and business perspectives.

In the broader context of Industry 4.0, digitization, data, and new types of IT infrastructures have become the ultimate drivers for innovation in the production engineering process. With a view to advancing design research into the digital era, the basic dimensions of design need to be connected with Industry 4.0 key principles for Design Engineering presented in Sec. 2.3. In concert, they will significantly enrich the DE4.0 research landscape of the future.

2.3 Industry 2.0 Key Principles for Design Engineering 4.0. Regardless of many variations in the definition of Industry 4.0 [17,38], the core principles are commonly agreed upon to allow manufacturers to investigate a potential transformation to Industry 4.0 technologies [39–41]. The following key Industry 4.0 principles are summarized with respect to design engineering.

(1) Connectivity, virtualization, and interoperability: These principles are empowered by digitization and IoT pervasively deployed in a human-cyber-physical production engineering environment. By connecting and digitizing business and production operations through cloud computing for software programs and data storage, interoperability facilitates the product or system to exchange contextual information with other products and systems. The design flow can utilize interoperability to extend the interaction between machines and humans beyond simple and defined cases. Moreover, digital

transformation makes possible many virtual resources to be from one or more physical resources. Through virtualization, the hardware environment of product realization can be simulated by creating digital twins of physical assets using data from sensors, while software is used to divide one physical server into multiple virtual servers that act like unique physical devices. Digital twins, or 3D models, are used to optimize machine performance, allowing what-if scenarios to be run and the impact of new equipment to be tested. They can also act as companions for physical objects for operators to view the real-time status of the machine, analyze performance, test solutions, and identify potential issues before they arise, and thus to extend the life of physical assets, uncover operation inefficiencies, reduce maintenance costs, and understand manufacturing systems better. The core benefit of virtualization is to reduce hardware costs and the number of physical resources needed. With virtualization, applications, desktops, servers, and data are no longer dependent on one physical device, thus improving reliability and enabling add-ons to be included when required. An holistic overview of the principal concepts, functioning, and main characteristics of this technology, as well as the main trends of operating, communication, and use based on various case studies are presented in Ref. [42].

(2) Big data and information transparency: A smart factory is capable of collection and analysis of data in real time, allowing decisions to be made immediately and at every moment. Real-time capability is not only limited to market research but also to internal processes such as the failure of a machine in the production line. Smart objects can identify the defect and delegate tasks to other operating machines, contributing greatly to the flexibility and the optimization of production. Big data and analytics are the core capabilities of real-time informatics driven by digitization and integration of vertical and horizontal value chains, as well as digitization of product and services, along with digital business models and customer access. Such information transparency afforded by Industry 4.0 provides operators with comprehensive information to inform decisions. It requires that information systems should be able to create virtual copies of the physical world by configuration of digital data into sensor data. For this to be achieved, raw sensor data must be aggregated with compatible context data.

(3) Decentralization, modularity, and interactivity: The ability of a cyber-physical system enables decentralized decisions to be made by the components of the system on their own and to perform their tasks as autonomously as possible. Only in the case of exceptions, interference, or conflicting goals, are tasks escalated to a higher level. The ability of a cyber-physical system to work independently facilitates modularity, such that in a dynamic market, a smart factory can adapt to new markets. It is useful when the smart factory must adapt fast and smoothly to seasonal changes and market trends. With modularity, a business can be split into small, well-defined teams that focus on specific elements of the business operation. A business that implements modular systems, such as software platforms for accounting or HR, allows the company to purchase only what it needs and add more in the future as needed. It is different from outsourcing as modular systems still need to be designed to interact with, and connect to, the rest of the business. The interactions among the modular units and their connections to the central business are coherently enabled through the cyber infrastructure and information sharing in the smart factory. In times of Industry 4.0, the associated networking of things provides new mechanisms and ways of interacting to be defined at both the process and product-related sides.

(4) Service orientation and networked resources: A cyber-physical system is running by offering services via the Internet based on a service-oriented architecture. In Industry 4.0, production must be customer-oriented. People and smart objects and devices must be able to connect efficiently through the Internet of Services to create products based on the customer specifications. Through the Internet of Services, the physical resources become networked and are organized cohesively in the virtual world.

In the context of current and evolving states of design engineering, and the key principles required for its success some opportunities and challenges for DE4.0 are described in what follows.

3 Opportunities and Challenges for Design Engineering 4.0

While Industry 4.0 mainly focuses on manufacturing and production, it is important to develop specific design guidelines that are implementable through Industry 4.0 technologies [43–45]. Designing and developing products in the era of Industry 4.0 is fundamentally different from principles in the context of system-level design. While system-level design also considers different technical domains such as mechanics and electronics, till recently it did not account for the networking between different elements such as products and machines. For a holistic approach to considering the challenges in product development concerning the integration of Industry 4.0, it is important to examine a dichotomy between Industry 4.0 principles and the human, artefact and process dimensions of design. In Table 1, a grid of key Industry 4.0 principles in correspondence to the artefact, process, and human dimensions of design is depicted. It provides a positioning framework of DE4.0 spanning nine strategic areas. These strategic areas represent many emerging issues and opportunities for DE4.0 research, addressing either the improvement of effectiveness (focusing on the artefact) or the increase of efficiency (focusing on the process) or the enhancement of satisfaction (focusing on the human), as elaborated below.

3.1 Smart and Connected Products. Many products that used to be standalone digital devices in the past are going to be connected as networked smart devices in the future. This means that smart products can communicate with each other and can generate significant customer benefits. Compared with a conventional product, the functionality and the possibilities of the business model are larger by a multiple for a connected smart product. Combination of multiple disciplines such as mechanics, software, electronics, and especially the integration of completely new business models, should make their way from being not cross-linked into a smart connected world. It is significant to intertwine digital and physical features across the whole product life cycle [46].

Table 1 Design Engineering 4.0 Strategic Areas in Line with Industry 4.0

Key principles of Digital Transformation for Industry 4.0		Strategic Areas of Design Engineering 4.0		
	➡	Artefact	Process	Human
Connectivity, visualization and interoperability	→	(1) Smart and connected products	(2) End to end digital integration	(3) Customization and personalization
Big data and information transparency	→		(4) Data-driven design	
Decentralization, modularity, and interactivity	→	(5) Digital twins and intelligent design automation	(6) Extended supply chains and agile collaboration networks	(7) Open innovation, co-creation, and crowdsourcing
Service orientation and natural resources	→	(8) Product servitization and XaaS	(9) Platformization for the sharing economy	

Traditional design efforts are mainly focused on how to enhance the interactions between designers and customers. Smart sensing and cyber-physical systems technologies make possible direct involvement of the customers early in the concept generation and evaluation processes, and to ascertain accurately customer needs through real-time product usage feedbacks. Envisioning the benefits of early customer and supplier involvement in the design stage, DE4.0 should perform as a decision framework of modeling and analyzing the interactions of product design with the upstream customer and market concerns and with the downstream product fulfillment issues. Product development will evolve from typical functionality-based products to *smart connected products* with embedded ICT components to provide massive product usage feedbacks [47]. Embodiment of a digital thread throughout design, production, and consumption/use is the core of developing smart and connected products.

A smart and connected product act as an *intelligent product/device* to tell future product in-use situations by collecting user data and product operating data directly from the physical products in real time. It is possible that a group of physical products can communicate and collaborate directly with one another. Furthermore, a physical product connected to the cloud-based environment can interplay with an intangible service on the Internet. A smart product can be monitored, controlled, and upgraded remotely [48]. The equipped sensor technologies make the product to be *aware* of condition information regarding the product and its environment. It is also equipped with control technologies to adapt the product autonomously in response to internal or external commands. At the back end, the smart and connected products integrated into modern production flows can self-process, store data, communicate, and interact within the industrial ecosystem. Starting from the earliest practice of enabling products to identify themselves via RFID, the products' capabilities to provide information have since evolved. Today a smart product not only provides its identity but also describes its status and life cycle history. Embedding computing algorithms and machine learning capabilities will enable these products to learn and optimize the outcomes at every production stage while providing valuable data for maintenance and troubleshooting in case of failures.

Key questions:

- How can the design process of smart products be directly influenced and improved through near-real-time analysis of vast amounts of user data automatically collated from prototypes and/or released products being used in diverse ecosystems of other interconnected smart products?
- To what extent will computers be able to autonomously shape design aspects of smart and interconnected products or conceive new innovative features based on user data analytics (autonomous or semi-autonomous data-driven design and innovation)?
- How can customer privacy and the ethical usage of data from interconnected smart devices be designed into such products (technical aspects) and the corresponding legal framework, including the General Data Protection Regulation and new policies governing the usage of smart and interconnected products across countries?
- How can user interfaces for and user interactions with smart products be designed so that they are intuitive and inclusive, and able to autonomously adapt in response to other smart products they get connected to (autonomous context awareness and adjustment)?
- Smart and interconnected products rely on standardized communication protocols and data exchange formats. How can these be designed into such products so that they can be autonomously updated over the air without requiring direct user interaction or IT expertise?

3.2 End-to-End Digital Integration. The new digital systems of Industry 4.0 gauge data from both physical and digital sources across the entire product realization process. While Industry 3.0 deployment of manufacturing informatics achieves a physical to digital transformation, the cyber-physical digitization in Industry 4.0 powers the physical act of product development, manufacturing, distribution, and performance within one ongoing cycle, which entails a *physical-digital-physical information value loop* [49]. Within this loop, real-time information and intelligence flow between physical and digital aspects of the product realization process. The physical-to-digital connection enables *vertical networking* of product development to rapidly respond to various changes that come as a result of shifting demands, stock levels or unexpected equipment faults. It is the leap from digital back to physical, from connected, digital technologies to the creation of a physical object that constitutes the essence principle of Industry 4.0 [50]. Smart factories are highly connected entities, with different systems being able to interact with one another and adjust their performance. The physical-digital-physical loops enables *horizontal integration* via a new generation of global value chain networks at a higher level of information transparency. Companies can locate and respond to problems faster. Such organization-wide networks can record information from all the operations including intralogistics and warehousing, to prototyping and production, to marketing and sales to downstream services. Every aspect of the product development process is logged and can be assessed and analyzed at any time. This end-to-end digital integration principle implicates a *smart product development* process and *model-based design systems engineering*.

First, many companies used to focus on product innovation, with limited attention to the chance of product development model innovation. Industry 4.0 indicates powerful new efficiencies by streamlining product realization processes in and outside of the R&D department through digital integration. Smart virtual product development has been advocated for rapid integration of diverse new technologies [51]. Smart connectivity of Industry 4.0 has inspired more and more business model innovations, often delivered by start-ups, which has gained significant market success [52]. Traditional companies need a change in product development capacity per discipline. For instance, the mechanical parts need to be reduced according to the share of functions, so that mechanical parts will take on in the future. By digitally connecting design processes and data across the organization, manufacturers can create a digital assembly line that stretches seamlessly from partners to the factory floor to customers [53]. In addition, DE4.0 calls for both horizontally and vertically integrated product development models [54]. Developing networks can be helpful for the necessary integration of the vertical value chain across the suppliers and customers. Interdisciplinary project teams lead to an integration of the horizontal value chain and to a better communication and collaboration without thinking and acting in silos [38]. Especially design project management needs to integrate employees from all hierarchy levels to integrate the different perspectives on the product specifications.

Second, digital integration in Industry 4.0 creates opportunities for smart design to be achieved through integration of product models, design methods, and decision support tools [45]. Components and product models in a cyber-physical production system are heterogeneous and span multiple disciplines, requiring multiple domain models to represent the physical aspects, requirements, architectures, behaviors, spatial-temporal constraints, and interfaces at multiple levels of abstractions [55]. Model-based design systems engineering utilizes formal and sufficiently complete models, processes, their environments, and their interactions. The goal of a model-based design systems engineering is correct-by-construction, where properties of the synthesized models of the designed system predict the properties of the implemented or manufactured system with sufficient accuracy. For example, OpenMETA is developed as an integrated tool suite to provide a manufacturing-aware design flow, which covers both cyber and physical design aspects [56]. Likewise, DARPA's AVM project emphasizes a fully integrated product model and component-based design flow for product realization [57]. For model integration, a large suite of modeling languages and tools are available for multiphysics, multi-abstraction, and multi-fidelity modeling and analysis, such as OpenModelica, Dymola, Bond Graphs, Simulink/Stateflow, STEP, and ESMOL. To integrate modeling languages for smart product development, mathematical models can bring together abstractions that are imported from individual languages and required for modeling cross-domain interactions. Both domain-specific modeling languages, like CyPhyML and FORMULA, and unified system design languages, such as SySML or AADL, institute a layered language architecture and specification of explicit semantics. These formal design systems engineering modeling languages are useful to act as an integration infrastructure of design software tools by creating and executing complex analysis flows, while enabling software-as-a-service using repositories and analytic services [58].

Key questions:

- How can digital design representation models and physical manufacturing systems and processes be integrated to realize the next generation of horizontally and/or vertically integrated Smart Computer-Aided Design and Engineering systems?
- How can Design for Manufacturability principles be advanced to include the latest possibilities brought about through digitization and smart processes (e.g., new Design for Additive Manufacture guidelines)?
- How can distributed physical design and manufacture environments be composed, managed, and controlled by autonomous software processes?
- How can the interoperability of Information Technology (CAD, CAE, etc.) and Operational Technology (manufacturing operations management, scheduling, etc.) be advanced? This is also knows as IT-OT-Convergence.
- How can software-defined cyber-physical networks be realized so the technical computing infrastructure for cyber-physical design and manufacture systems can entirely be brought under control of software, without human interventions?
- How can cyber-technological change and social change be integrated to foster the democratization of design, manufacture, and innovation?
- How can the disruptive innovation capability enabled by social product development (SPD) be integrated with the disruption technology capabilities in industry?

3.3 Customization and Personalization. *Design for mass customization* by product family design and platform development has been well recognized in the age of Design 3.0 [59,60] The digital integration in Industry 4.0 offers unprecedented opportunities for satisfying various requirements and business goals of diverse stakeholders involved in the product realization value chain. The general gist of product customization is through configuration of different product modules within a well-planned product platform, which is mainly based on retrospectively known customer requirements in the target market segments. DE4.0 makes it possible to involve customers early in design and proactively plan marketing-engineering interfaces in product line design, while optimizing economics of scale and scope through coordinating not only the product platform and modules but also the corresponding platforms and modules of product fulfillment including processes and engineering logistics [61]. *Customer integration and marketing-engineering interaction with product family design* are suggested to be an important area of DE4.0.

In addition, the digital integration extends the traditional landscape of customer satisfaction to broader dimensions, for example, identifying product characteristics that cause different degrees of satisfaction among different customers, understanding the interrelation between the buying process and product satisfaction, determining the optimal amount of customization and customer integration, explaining the key factors regarding the value perception of customers, and justifying an appropriate number of choices from the customers' and marketing perspective. Equally important are customers' decision-making processes when interacting with product families and in turn developing proper fulfillment capabilities. Hence, it is important to support decisions of customers at the front end, which coincides with consumer behaviors in business systems based on early customer involvement in the product customization process. At the back end, the smart connectivity *extended platforms for comprehensive product families* through a synergy of increased customer-perceived value and cost reduction in design, manufacturing, and the supply chain [36]. Comprehensive product families share a multidimensional core of assets such as standardized components, manufacturing, supply and distribution processes, customer segmentation, and brand positioning. To support coordination of the demand and supply chains with product families, the platform strategy is extended to the entire continuum of product fulfillment, including customer platforms, brand platforms, product platforms, process platforms, and logistics platforms. The extended product development platforms facilitate the enterprise to create dynamically stable capabilities that enable the firm to adapt, integrate, and reconfigure the manufacturing skills and competences, to adapt to a changing business environment and to respond to customers' requirements in a timely manner.

While customization hinges upon differentiation of product offerings through combinations of a large variety of product and marketing features, personalization is anchored in user experience through fulfillment of usability in terms of functional, affective, and cognitive customer needs [62,63]. Smart sensing and ambient intelligence technologies enable acquisition and analysis of customer affective needs [64] and support intelligent reasoning in human-centered design [35]. For example, physiological measures are widely recognized to be an objective user experiment instrument for analyzing customer affective/emotional needs [65,66], predicting task intent in human–robot interaction design [67], and recognizing user intents in robotic control design [68]. *User experience design* lends itself to be a critical pillar of *design for mass personalization* [32]. In addition, the smart connectivity pervasively available in a cyber-physical operational environment enables a cohesive collaborative network of fulfilling product or service personalization among small-to-medium enterprises (SMEs) and networked resources to achieve low volume or even one-of-a-kind production or service delivery [61,69,70]. Moreover, the massive data generated through user interactions with the cyber-physical system empowers product informatics for personalization. For example, personalization design needs to envision a product's use environment-based customer need identification, in which explicit modeling of the product usage context's influence on customer preference and product performance is critical [71]. User generated contents such as online customer reviews reflect observations of a product in use as a way of gathering raw data from customers [72]. The product usage context implies a combination of application conditions and product's operating environment for which a product is to be used through interaction with the user(s) and the objects in the environment [73]. Data mining and machine learning from massive data generated by users enables identification and prediction of latent customer needs for personalization design [74] or developing open product and service architectures to be deployed as a cyber-physical co-development model to support product personalization [48]. Furthermore, Industry 4.0 digitization and enabling technologies tremendously enhance verification of personalization design through immersive virtual prototyping [75], user authentication [76], and scenario learning of use cases [77].

Key questions:

- How can smart sensing and ambient intelligence technologies be leveraged to enable acquisition and analysis of customer affective needs, thereby identifying product characteristics that maximize degrees of satisfaction among different customers?
- How can customers' decision-making processes when interacting with products and product families be better understood,

and how the resulting knowledge can be used to develop robust fulfillment capabilities?

- How can marketing-engineering interfaces be proactively planned by involving customers in the early-stage design through Industry 4.0 technologies? How can data mining and machine learning from massive data generated by users enable identification and prediction of latent customer needs for personalization design?
- How can the demand and supply chains be coordinated with product families? How can the design of product platforms be carried out in an integrated manner with the design of manufacturing processes and fulfillment logistics? How can the platform strategy be extended to the entire continuum of product fulfillment, including customer platforms, brand platforms, product platforms, process platforms, and logistics platforms?

3.4 Data-Driven Design. Companies embracing Industry 4.0 must deal with both prescriptive and predictive analytics. Big data are essential for optimizing performance at every stage of development, from design through production. Performance data from the end-use environment can also lead to engineering design changes for future versions. Big data are also needed to identify and analyze consumer trends, which can directly impact what engineers make and how they make them. The characteristic of big data and information transparency in Industry 4.0 intensifies a data-driven approach to continuous design improvement and next-generation product prediction [47]. The *data-driven decision-making* process exemplifies an information feedback loop of collecting, storing, and analyzing data from customers and end-users of the products, with the goal to discover new needs or identify changes in usage patterns, and in turn to provide information about new product offerings back to the customers [78]. By exploiting large, versatile, and highly contextualized product through-life data, design engineers can harness their organization's competitive edge by uncovering patterns, novel insights, and knowledge through data-driven design [79]. It is desirable to make use of feedbacks from ex-post-facto data to investigate the patterns and behavior relationships underlying the actual product usage information [80]. While data-driven design makes better informed decisions possible for developing better products, enormous and multiplex user- and product-generated data brings about many challenges, alongside unmatched opportunities, for advancing the theory, methods, tools, and practice of engineering design for products, systems, and services [81]. This *data-driven analysis* approach is motivated by the belief that, when we know how customers are using the products, we can meet their needs better. The basic rationale is to base design decisions on facts, but not assumptions, which coincides with an inverse thinking of problem solving [82]. Therefore, a data-driven analysis approach is envisioned to be a mainstream business model for companies to innovate their product development and take a proactive approach to discover driving factors underlying product in-use situations based on analysis of vast product usage information [83].

Monitoring and gathering product usage data serve as the basis for performance degradation assessment and data-driven design improvement [84]. Combining the product design with customer research based on a data-driven analysis approach may provide information to guide the search space of design concepts and extract the trend of customer preference for future product design accurately [85]. While data-driven design is appealing, the essential impact and best form of data-driven analysis for design theory and methodology have yet to be fully understood. The prevailing methods of data-driven analysis essentially strive to exploit user generated content or experiment and simulation data to approximate good surrogate models for better modeling of the design problem. The challenge is that the design process itself cannot be driven by whatever data per se; but rather it is design knowledge and informatics acquired from data that can support designers to make informed decisions [73]. In this sense, *data-informed design* may reveal the essential characterization of knowledge-based design decision-making underlying data-driven design [86]. For example, Kusiak [87] points out that the most important toll gates of innovation are the generation of new ideas and their evaluation, and thus a data-driven analysis approach to innovation helps improve designers' limited ability to generate and evaluate many potential innovation alternatives. Lin et al. [88] outline a six-phase UNISON framework for data-driven innovation to capture user experience and preference among the factors of product form designs to derive useful rules, and in turn to explore new design concepts to enhance product user experience. Jiao et al. [89] envision a data-driven analysis approach to product portfolio planning by incorporating peer influence of social network effects. Ma and Kim [90] propose a predictive data-driven model for determining the optimal product family architectures with customer preference data by k-means clustering. Ma et al. [91] exploit the time-dependent product usage data for design improvement by assessing product function degradation based on collected time-dependent data of performance features.

To summarize, data-driven analysis consists of both prescriptive and predictive analytics. Prescriptive analytics makes use of machine learning to help decide a course of action based on predictions anchored in simulation of the future state. Prescriptive analytics works with predictive analytics to determine outcomes based on limited information.

Key questions:

- How can data-driven analysis be used to extract customer preference trends and to establish the search space of future product design?
- How can data-driven analysis approach to innovation help in improving designers' limited ability for generating and evaluating large numbers of potential design alternatives?
- How can a data-driven analysis approach be used to incorporate peer influence on a social network during product portfolio planning?

3.5 Digital Twins and Intelligent Design Automation. Design used to be practiced through a tedious iterative and rigid development process, in which designers and engineers elicit customer requirements, generate design concepts, create physical forms, verify designs virtually and physically to determine how they perform, and refine designs until they meet the specifications, while keeping time and budget under control. With decentralization of decisions through modularity and digital interactions between the cyber and physical entities, a new wave of *intelligent design automation* [92] becomes real in DE4.0, in which engineers dedicate their creative efforts to what they are building rather than how to follow the workflow [93]. By utilizing the web of digital threads, designers and manufacturers can seamlessly obtain and exchange part design and manufacturing information, thereby promoting cyber design and digital manufacturing to establish a design chain in both the cyber and physical spaces [58]. Design automation has evolved as a human-cyber-physical network wherein multiple manufacturing resources are pooled over the internet to provide design and production services that could be located at remote sites [94]. This information, when gathered concurrently during the design phase of products and incorporating AI and machine learning algorithms, can assist in making judicious downstream decisions such as manufacturing, assembly, and testing [95]. For example, ontologies are well known for design knowledge modeling by representation and integration of knowledge related to decision-based design of both products and their designing processes, enabling a knowledge-based platform for decision support in the design of engineered systems [96,97].

While embracing big data and analytics, intelligent design automation hinges upon life cycle product data management that integrates product information exchange and intelligent decision support within a coherent framework of design knowledge management and data value extraction, such as a data-information-knowledge-wisdom (DIKW) pyramid model [98]. For this purpose, the *digital twin* is a newly emerging and fast growing technology that enables digital integration of the physical and virtual worlds [99]. A digital twin is a virtual representation that serves as the real-time digital counterpart of a physical object or process. Though the concept originated earlier, the first practical definition of digital twin originated from NASA in an attempt to improve physical model simulation of spacecraft in 2010.

A digital twin essentially entails an integrated multiphysics, multiscale, probabilistic computational model for engineering simulation of a complex product, functioning to "mirror the life of its corresponding physical twin [100]." It serves as a bridge between the physical world and the digital world by leveraging CAx systems in the digital world and IoT in the physical world [101]. Digital twins and big data analytics are mutually reinforcing technologies to account for smart design and manufacturing in twofold: a physical product can be made more intelligent to actively adjust its real-time behavior according to the recommendations made by the virtual product, whereas the virtual product can be made more factual to accurately reflect the real-world state of the physical product [102,103]. Digital twins tremendously boost intelligent design automation by incorporating computational intelligence. Utilizing digital twins, Computer-Automated Design (CAutoD), commonly known as virtual rapid prototyping, has emerged as an extension of traditional CAD by implementing biologically inspired machine learning techniques to intelligently search and evaluate the design space for innovative and optimal solutions [104].

Application of digital twins to the multiple domains of product realization further strengthens *co-design and co-development* of the product life cycle. While digital product twins with integrated production knowledge are developed to support DFX, digital production twins with integrated product knowledge enables function-oriented production control [105]. A digital twin model is widely used for usage monitoring of complex engineered products such as an engine [106]. While the physical product in use is monitored in real time, the product digital twin continuously records the product usage status, use environment data, operating parameters, etc. As a result, users can keep abreast of the latest state of the product, while the designers run the virtual model to simulate the operation conditions of product in different environments. A high-fidelity digital twin model supports smart MRO planning based on the prediction for health condition, remaining life, and fault diagnosis, while reinforcing design strategies for proactive maintenance to avoid the sudden downtime [107].

Key questions:

- How can feasible design concepts be generated by computers?
- How can design concepts generated by humans be evaluated by computers?
- Is it possible for computers to learn and display creativity in the generation of design concepts?
- How can digital twins of humans be integrated with digital twins of production engineering systems and processes, for example in the context of training robots to collaborate with humans on assembly lines, or even in the context of the design process?

3.6 Extended Supply Chains and Agile Collaboration Networks. The fusion of cyber and physical product realization in Industry 4.0 leads to virtual structures in the value chain and supply chains, which require organizational and managerial tasks for relevant cross-company operational processes to be fulfilled through distributed networks of manufacturing, logistics and distribution. Prudent design of these networks and supply chains is essential to insure fail-safe performance [108]. Management tasks are realized and controlled by information flows within the connected enterprise networks, and they are running parallel to the physical supply chain flow. Consequently, the value streams throughout the extended supply chains require appropriate design of digital fulfillment in the cyber platform to be able to control the parallel information streams and to handle the execution of related business operational tasks [109].

Extended supply chains in Industry 4.0 are formed by agile collaboration networks and connected product design chains. *Agile collaboration networks* describe the direction of horizontal integration, allowing manufacturers to focus on their competencies by offering customized products in any market [110]. Connected design chains are formed through vertical supply networks allowing the integration and automation of physical processes and providing increased transparency [111]. *Design of smart supply chains* facilitates decentralized production logistics control and data-driven operational excellence [112]. Decentralized production logistics control is formed by a network of machines with self-organization and process configuration allowing materials handling in production control to be decentralized [113]. The rich data generation of the production and logistics processes provides a solid foundation for achieving data-driven operational excellence [114]. Following a design science approach, Schulz and Freund [115] examine the implications of blockchain and the industrial IoT in supply chain management for Industry 4.0. New opportunities exist for designing sustainable supply chains in line with smart and connected product realization processes in Industry 4.0 [116,117].

Design of digital supply chains must be aligned with the virtual value chain planned for product realization within connected enterprise. For effective supplier management, the dynamic reconfigurability of supply networks that Industry 4.0 promises requires re-examining service-level agreements with upstream and contracted suppliers. Dedicated capacities, enhanced risk profiling, IP protection, and the reliability of materials will all need to be included. Supply chain reconfiguration design is closely coupled with product platforming and product family design decisions [118]. Supply chain visibility is important to respond as quickly as possible to planned and unplanned events in order to increase productivity and reduce risks [119]. Product architecting, production planning, and supply chain decisions must be coordinated according to the digital threads of product realization in DE4.0. Demand forecasting and product planning will be tremendously improved through big data analytics enabled by smart and connected product realization. Supply chain design requires a connection of production capabilities with the logistics decisions based on a clear understanding and translation of fluctuating demand patterns into targeted production units [120]. To achieve agility and supply resiliency without compromising time to market, supply networks need realignment based on the supply network design that considers a digital product realization value chain. A Gartner study showed that this is an area where many companies fall short of expectations [121]. As smarter factories take root, ensuring that alignment is done in a holistic way, not just within manufacturing or logistics, will be critical. Digital supply chain operations need to be planned within the enterprise product innovation platforms. New physical devices, such as products, tools, or even factory equipment, will have interconnected technologies embedded in them. The way things are manufactured will require new thinking and what new IT calls product innovation platforms, which aim to define and design products but also to manage product lifecycles [122].

Key questions:

- What are DE4.0 principles and methods to be applied to ensure fail-safe performance of the entire virtual value chain for product realization, which includes product design, production planning, and the supply chain?
- How can the rapidly changing demand forecasts be used to dynamically adapt the value chain?
- How can the effects of disruptions in any part of the supply network be rapidly mitigated through rapid and holistic redesign of the product, the manufacturing process, and/or realignment of the supply network?

3.7 Open Innovation, Co-Creation and Crowdsourcing. The main drivers of DE4.0 are long-term innovations, especially for business model innovations integrating with vertical and horizontal capabilities and co-creation strategies, which exemplify a collaborative strategy to grow together with customers and stakeholders [123]. Industry 4.0 ultimately targets to achieve individual production down to lot-size one at costs close to mass production. To do that requires a tight value-network integration within the production line but also with suppliers via decentralized control of production processes. Not a new concept though, open innovation has paved the way for using collaborative innovation to its best advantage in Industry 4.0. It facilitates design of a hyper-connected business that includes manufacturers as part of a broader and more integrated value chain in an ecosystem of the right stakeholders [124]. In Industry 4.0, ever fewer organizations can rely exclusively on an internal R&D process to generate innovation. A model of cooperative innovation as an ecosystem is increasingly critical to drive value for all stakeholders involved [125]. DE4.0 implements an innovation pathway as co-creation, such that strategic partners actively collaborate to create and deliver customer-centric products and services that capture greater values, more rapidly and at lower risk than traditional product-development practice [126]. Value co-creation is rooted on a fundamental concept of human-centric innovation motivated by Society 5.0 [127], which aims to enrich the welfares of both workers and customers, while generating growth and real business values. DE4.0 adopts a holistic approach that leverages upon three critical pillars: human empowerment, creative intelligence, and connected infrastructure [128].

In the context of integrated materials, products, and manufacturing process design, digital co-design have been advocated as the capability of a network of participants in the value chain, including material scientists, systems designers, software developers, and end customers, to come together and share material/product/manufacturing process/market data, information, knowledge, and resources instantly and in an integrated fashion, thereby to collaborate and facilitate a cost-effective co-creation of value supporting open innovation. Opresnik et al. [78] present a digital co-design architecture anchored in the decision-based design paradigm, while integrating product and process models, design methods, and decision support tools. Industry-inspired example problems are reported to demonstrate the utility of the digital co-design. A designer/decision-maker/user can carry out various design tasks systematically in relation to digital model development and integration [129], co-design problem formulation and goal-oriented inverse design exploration [130], uncertainty management and robust concept exploration [78], and knowledge-based co-design guidance and decision support for the users using a cloud-based decision support platform [130].

Collaborative design has been well developed in the age of Design 3.0 to deal with engineering decisions as collaborative negotiation [131] and support design with customers by iterative decision-making [132]. Open innovation and value co-creation in DE4.0 exemplify a new strategy of *design by customers* through crowdsourcing [133]. Crowdsourcing has been recognized as a connecting approach to installing the open business model by transcending organizational boundaries in order to leverage resources and capabilities across distributed stakeholders [134]. Different from the conventional strategy of outsourcing in supply chain management that emphasizes how to assign a task to a designated agent, crowdsourcing utilizes an open call to a crowd for maximally exploiting the external resources [135]. *Crowdsourcing* entails a new value-based model as a social-economic cyber platform in which products and services are created and delivered in an open, collaborative, and distributed manner [136]. Acting as a cyber transaction platform, crowdsourcing is a large problem-solving model that utilizes Internet technologies to coordinate, negotiate, and manage the crowds for performing the specific organizational tasks of product realization [137]. It entails a superior broker system to coordinate the information and material flows among the stakeholder crowds and therefore enables the companies to crowdsource their peripheral activities and concentrate on their core competitive [138]. Product realization by crowdsourcing takes advantage of a digital crowdsourcing platform established in the cloud-based cyber space [139] which makes it possible for the crowdsource to explore external knowledge and resource while coordinating the activities of designers and manufacturers as a collaborative product fulfillment network [140].

Key questions:

- How can data from real-time events be infused into design and manufacture processes? For example, how could the design of product packaging be adjusted to represent the shape of the mascot of a football team that won a derby?
- How can crowdsourcing be effectively leveraged for both not-for-profit and industrial/commercial design processes?
- How can Open Innovation be extended to include other elements of social product development (Crowdsourcing, Mass Collaboration, Cloud-based design and manufacture)?
- How can the various models of crowdfunding be leveraged in the design of commercial products?
- How can vast amounts of customer feedback on online platforms be leveraged to advance customer co-creation?
- How can data-driven approaches such as social network analysis be used to analyze and improve the behavior and performance of design teams to identify designers or teams of designers whose activities is likely to lead to breakthrough innovations more often than that of others, or to identify team members that hinder the innovation process through design solution fixation.

3.8 Product Servitization and Anything as a Service (XaaS).

Many manufacturing companies have developed product-service systems (PSS) as a means to enable collaborative consumption of both products and services with the aim of pro-environmental outcomes [141]. Such a servitization business model enables sustainable product development that has the potential to minimize environmental impacts of both production and consumption [142]. An Industry 4.0 factory is equipped with ubiquitous connectivity in the manufacturing environment, allowing collection of significant volumes of dispersed information to support distributed decision-making in fulfilling manufacturing tasks [8]. The new open manufacturing capabilities enabled by crowdsourcing platform [143] will create opportunities for transforming and expanding the manufacturing sector by developing intelligent cognitive assistants to perform as decision support systems, which facilitates the fulfillment of *manufacturing as a service (MaaS)* [144]. The compelling need for accommodating a dynamic and collaborative network of manufacturing services has a broader implication for a service-oriented paradigm to be deployed as X-as-a-service (XaaS) and extended to the entire manufacturing regime to act as service manufacturing [145]. Another implication is dedicated to social manufacturing [146] that aims to take advantage of the interactive relationships among the manufacturer crowds to foster a manufacturing service network as an autonomous organizing process. The trend of cloud-based design and manufacturing offers a framework of connecting smart entities across a population of companies, thus enabling a demand-capacity matching mechanism to serve collaborative product realization [147]. Crowdsourced manufacturing enables fulfillment of MaaS through a cyber platform based on cloud-based design and manufacturing [143] which is organized as a dynamic resource sharing mechanism among the manufacturer crowds while engaging more manufacturer population in the MaaS network [148].

Consistent with the service orientation principle underlying MaaS and PSS, XaaS constitutes an important aspect of design thinking in Industry 4.0. Servitization is enacted through selling solutions and outcomes to the customers, rather than selling tangible products. Instead of just providing the means to fulfill the user's needs, manufacturers are now delivering the actual value out of that tangible object [149]. For example, Rolls Royce has introduced "CorporateCare," an accessory and engine replacement service. With sensors proactively predicting maintenance requirements for the engines and a lease plan for engines during plane maintenance, Rolls Royce can offer proactive engine rental services [150]. This allows customers to focus on their core businesses while reducing their risk. The sensors are used not only once a product is delivered, but also they are put to use in the manufacturing phase to monitor their progress as they move through the production line, achieving a new business model of Engine-as-a-Service (EaaS).

Industry 4.0 opens up the possibility to implement comparable *product as a service (PaaS)* business models also for complex products involving cross-company operations and a complex supply chain owing to the power of internet-use and cyber-physical systems. It makes the full production process traceable and transparent so that life cycle oriented business models like a PSS can be realized also for sophisticated products [151]. Such a PaaS business model represents the realization of a service design concept where the customer does not primarily purchase or own a product itself but rather buys the service the product is realizing with the consequence that the product design changes into servitization design [152]. In this regard, product servitization represents sustainable design since not the material product stands in the focus of the product value chain but the service realized by the product. Nevertheless, new challenges exist for successful PaaS design solutions regarding how to be connected to a strong and coherent brand identity, as well as the IP and ownership issues in practical PaaS business operations [153].

Key questions:

- How can products be redesigned so they become product-service systems that add value to the customer experience in the context of smart and interconnected consumer ecosystems?
- How can design and other product realization processes and associated systems be made available to both the general public and industry on a pay-as-you-go basis?
- How can computers on demand identify and configure appropriate resources and tools required for a product creation task based on the IoT and IoS?
- How can product realization-related services be registered, managed, offered, and provided through online platforms?
- How can product realization-related services composed by computers be validated to meet industrial certification requirements?

3.9 Platformization for the Sharing Economy. With evolutionary innovations based on smart and connected hardware and the Internet+ business ecosystem [154], Industry 4.0 fosters a wide range of disruptive innovations that have the potential to fundamentally change the industry landscape. In particular, a *sharing economy via service-providing digital platforms* is emerging and holds huge opportunities for the manufacturing world [155]. The sharing economy is also referred to as the access economy, crowd-based capitalism, collaborative economy, community-based economy, peer-to-peer (P2P) economy, platform economy, renting economy, and on-demand economy [156,157]. The sharing economy differs from the traditional maker economy in the business model design for reallocation of firm activities to external partners [158]. The firms used to be operated as a transaction-oriented manufacturer with focus on production and co-fulfillment of manufacturing activities based on physical product and process platforms. In contrast, a sharing economy firm works as a sharing-platform operator and focuses on consumption rather than production. It servitizes the product realization process through open design and open manufacturing over a cloud-based digital platform in the cyber space to coordinate the physical flows of product fulfillment among many co-creation XaaS providers [133]. The sharing economy is a socio-economic system built around the sharing of resources [5]. It includes the shared creation, production, distribution, trade, and consumption of goods and services by different people and organizations [6]. These systems take a variety of forms, often leveraging digital platform-driven crowdsourcing to empower individuals and corporations with virtual product realization information that enables distribution, sharing and reuse of excess capacity in goods and services [140].

This strategic area of DE4.0 calls for innovative design of suitable platform business solutions, which is very challenging because of the complexity of a wide range of possible business models, and many different players with varying interests and motivations. This is an important area that design innovation can find new opportunities. For example, a new process is being developed using virtual Minimal Viable Products (MVP) and the Build-Measure-Learn cycle in a process inspired by Google Ventures Design Sprints to understand market opportunities and involve all stakeholders early on [159]. A MVP traditionally would be defined as the bare minimum feature set required to release a product or service commercially. An example of a virtual MVP is the landing page built as a mobile App for Bosch Healthcare Solutions to investigate the potentials of an emergency service called "Lifebuddy." Design solutions of a sharing platform also need to test the value proposition, the pricing model, and the market viability of a product or service before building anything. It is also helpful to work with various players in the Business-to-Business (B2B) field to develop platform business solutions. It is common that companies fear of working with competitors, but when traditional companies are entering the platform world, today's competitors have to become partners and customers. If not, it is likely to end up building another dead silo solution. To generate enough traction for the platform to become relevant, co-creation, especially when led by an external design organization, can help to overcome corporate borders and offer a neutral playground, where competitors meet to discuss joint opportunities [160].

Design for platformization aims at a new platform-based, digital product together with complementary ICT services, indicating a significant application area of product informatics. Firms move from producing and selling physical products with at most product-related services toward digital products with related digital services. The meta-dimension of value capture moves from one-time sales to continuous subscription fees, in which customers do not pay for the ownership of a physical product but for its availability [161]. The meta-dimension value chain shifts from mass production of physical products toward mass customization of digital products [162]. External developers thereby play a more important role in product development and design [163]. Based on extensive industrial case studies, Lu et al. [164] summarize two platformization strategies. Product-related platformization describes how firms use their experience from manufacturing and selling asset-intensive machinery and turn it into a new digital product. The new offering primarily addresses unsolved customer problems. In contrast to product-related platformization, process-related platformization makes use of a firm's experience with internal processes and smart production and transforms it into a new digital platform involving many XaaS providers. The value proposition is an integrated solution of a digital PaaS rather than solving other customer's problems. Firms are more focused on service and support rather than intermediating [165]. For example, the GE Software Center has developed the IoT platform Predix as an internal solution for machine operators and maintenance engineers to reduce GE machine downtimes and to schedule maintenance checks more profitably [166].

Key questions:

- How can product-related and process-related platformization strategies be designed, which rely on value capture through subscription fees, in which customers do not pay for the ownership of a product but for its availability?
- How can external developers be engaged and incentivized to participate, thereby enriching the platform over time?

DE4.0 bears the potential for disruptive and potentially seminal changes in the way new products and product-service systems of the future may be brought about. In Sec. 4, we highlight some promising opportunities for research in DE4.0.

4 Opportunities for Design Engineering 4.0 Research and Education

As an area of engineering, design research focuses on the principles, theory, and method for understanding and improving the process of design to facilitate the creation and realization of new products and technologies [167]. Three basic dimensions of design, namely, human, artefact, and process postulate the subject matters and scopes of fundamental design research. Research in Engineering Design is grounded in theory and aims to advance scientific knowledge about design systems engineering as a discipline [168].[3] The DE4.0 principles have profound implications in identifying future directions for design research. Centering around the main theme of DE4.0, the emerging issues and outlooks for future research can be conceived from the human, business, system, and cybernetics perspectives and driven by IoX, as shown in Fig. 1. These strategic directions are inspired from the IEEE's system, man, and cybernetics perspectives toward human-system integration [169] and coincide with the core elements of a strategic engineering design program [31].

4.1 The Human Perspective—Design for User Experience. *(1) User Experience Design toward a Product Ecosystem:* Deployment of smart and connected technologies makes many new products being introduced to the market that they are no longer islands of their own to fulfill self-contained functionality. A modern product like a smart phone works not only because of its inherent industrial and interface design, but also because of the ecosystem in which it "lives" [170]. Likewise, the MyFord Touch exemplifies a product ecosystem that has been designed to enable personalized in-car experience in the form of human interactions with the entire interior environment [161]. Along the same lines, a Xerox customer can choose to either purchase a printer with potentially a service plan, or simply a printing service, where the printer is located at the customer's facility but not owned by the customer any more. These are all examples of a more holistic view of filling the customer need. As customers become more connected, products and related services are increasingly knitted into a larger ecosystem of touchpoints. The physical product is not alone, while other factors can be conducive to the users' emotional and hedonic experience, and in turn contributes to the value added [171]. This results in blurred boundaries between products, services and networks. It is often UX that makes product ecosystems appealing in many industries [172]. We have been convinced by the trend of product value fulfillment progressing from traditional function-focused product and service fulfillment to nowadays customization and personalization [62].

Pine and Gilmore [173] have envisioned an experience economy underlying this trend, which has indeed come to fruition in many industries. Product design traditionally copes with physical products and emphasizes mainly functional requirements, yet with limited consideration of customers' affective and cognitive needs or roles in decision-making [174]. It is therefore imperative for product design to bring in the human-system interaction explicitly [175,176]. Product ecosystem design for UX deals with a dynamic unit that consists of all interdependent products and users, functioning together with its surrounding ambience, as well as their interactive relations and business processes [63]. There are many fundamental issues that deserve scrutiny in relation to user-centered design and emotional design. An important research question to be addressed is regarding a deeper understanding of human-product-ambience interaction [64]. New opportunities exist for identifying promising topics for UX design research, such as modeling and analysis of customer affective and cognitive needs using augmented intelligence technologies [66].

(2) Cloud-based Computer-Supported Collaborative Work (CSCW) for Future Work of Designers: The human dimension of DE4.0 highlights the importance of user experience not only for customers as end-users at the front end but also for multiple stakeholders at the back end of product realization. Working within a human-cyber-physical system environment, the experience of designers becomes critical for developing computer-supported cooperative work [177,178]. As unveiled by the NSF's big idea on future of work at the human-technology frontier [179], the future work of designers is challenged by having to work with exponentially growing techniques. It is important for convergence research to understand and influence the impact of AI and automation technologies on designers and design work, understand and develop the human-technology partnership to augment human cognition, illuminate the emerging socio-technological landscape, understand the risks and benefits of new technologies, and foster CSCW that promotes designer well-being. Many research opportunities exist for understanding how designers work within groups and organizations and the impacts of technologies on those processes, for example, for the case of open design [180]. Understanding of the characteristics of interdependent group work will contribute to the objective of designing adequate computer-based technologies to support designers' cooperative work.

Over the years, CSCW research has identified a number of core dimensions of cooperative work, including awareness, articulation work, and appropriation (or tailorability), which have largely been derived through the analysis of existing systems [177]. However, the complexity of the domain makes it difficult to produce conclusive results, as the success of CSCW systems is often so contingent on the peculiarities of the social context that it is hard to generalize. For example, one of the most common ways of conceptualizing CSCW systems is to consider the context of a system's use [181]. Relating directly to the core of cyber-physical product creation, cloud-based CSCW has emerged as a promising service-oriented product development model [166] in which service consumers are enabled to configure, select, and utilize customized product realization services ranging from computer-aided design software to entire reconfigurable manufacturing systems. Noteworthy research problems can be formulated to examine the potential benefits of cloud-based CSCW, such as ubiquitous access to design and manufacture resources, on-demand scalability, multi-tenancy, increased resource utilization, reduced capital cost and complexity, reduced maintenance and personnel cost, accelerated time-to-market, as well as attractive pricing [147].

(3) Social Product Development for Democratization of Design, Manufacture, and Innovation: Delegation of design used to be a pragmatic systems engineering solution to managing a complex product development project through outsourcing. It shifts various design responsibilities to a general contractor, outside of a formal design-build contract, by way of the contract, specifications, or directives of the owner, all of which result in exposure to the general contractor when the delegated design is a problem or is perceived to be a problem [182]. DE4.0 enables a service-oriented product development model, in which service consumers are enabled to configure, select, and utilize customized product realization services ranging from computer-aided design software to entire reconfigurable manufacturing systems. This extends the design delegation principle to become social product development, i.e., to offer or utilize anything needed to take an idea for a new product all the way from conceptualization to production via the IoT and XaaS. It encompasses several exciting phenomena such as crowdsourcing, open innovation, and mass collaboration [7] but is a relatively undeveloped and unexplored area within both academia and the context of technology transfer.

The increased affordability of 3D printing has been one of the most significant motivators for the democratization of design, manufacture, and innovation. The democratization of design, manufacture, and innovation defines empowerment of the masses in social product development. It is the process whereby power has been taken from those with wealth and given to those with innovative ideas. Previously, the main barrier that stood before these individuals was manufacturing, but now affordable 3D printing means

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prototyping and production is easily accessible. Key issues worth investigating include the sociotechnical aspects [183] and how to utilize the cloud-based computational infrastructures to support social product development for democratizing design, manufacture, and open innovation. More challenging issues and research questions to be addressed include integration of digital twins and digital threads, integration of models and simulation tools spanning processes and length scales in line with different domains in axiomatic design, defining computational workflows that support decision-making and span multiple activities and users, defining modular, reusable sub-workflows for specific processes, design of cyber-social decision networks, implementation of reliable and stable connections to external databases on materials, products, processes, and customer surveys, development of knowledge-based assistance mechanisms to enable different types of users to participate in design-related decision-making, security of data and privacy control, capability to explore the design and solution space for implementation of systems that conform to Industry 4.0 construct, and robust implementation of Industry 4.0 construct through dynamic and cost-efficient reconfiguration of manufacturing processes during their operations.

4.2 The Business Perspective—Design as Strategic Engineering. *(1) Smart innovation and business value chain design:* A smart product itself is a cyber-physical system providing new features and functions based on connectivity and smart services. It opens the way for the business growth where new technologies offer and enable the digitization of delivery services. Smart innovation comprises extended innovation and connected life cycle innovation. Extended innovation has two streams of information that comes from the inside out and the outside in. Advanced product life cycle management systems form the connected life cycle innovation, which can be accessed from anywhere, especially through mobile apps. Achieving smart innovation is implemented as hrough-engineering across the entire value chain, in which all the product development and manufacturing activities are integrated and coordinated with the product life cycles. New synergies emerge between product development and production systems through two types of value chain integration.

The first is vertical integration whereby all the systems in the traditional automation pyramid are affected, from field and control levels to production level, operations level, and enterprise planning level. Vertical integration will make the traditional automation pyramid view disappear. The same goes for several systems and applications across these various levels. Other systems such as Enterprise Resource Planning (ERP) will dramatically change while still others will be replaced by rapidly emerging applications in the scope of Industrial IoT platforms, specifically manufacturing platforms and vertical platforms for various tasks and use cases in the many aspects of industrial applications that get ever more features and become combined in an interoperable systems-of-systems approach and by digital transformation platforms and business applications where IoT platforms and functionalities are integrated into.

The second is horizontal integration which is not about the hierarchical view of several systems as in vertical integration but about the end-to-end value chain, from supplier and the processes, information flows, and IT systems in the product development and production stages to logistics, distribution, and ultimately the customer. Decentralized intelligence in manufacturing impacts various systems employed in industrial markets and in the end is all about data and how, why and where it is used at the right time and right place for the right reasons to paraphrase the DIKW model [98] from data to knowledge with the additional layer of decisions for actions.

More research issues worth of investigating are related to semi-autonomous and autonomous decisions in an Industry 4.0 system. It is important to examine the essence of the business value chain of self-organizing plant and autonomous production [184]. It is of particular importance to justify to what extent for value added in product fulfillment when adopting as much automation as possible with IoT, artificial intelligence, the new integrated systems, advanced analytics, and so forth that all play a role in the business value chain. New value stream mapping methods are deemed to be an important research opportunity for a holistic analysis of design value streams in the digital age [39]. Design of Industry 4.0 business models is crucial for new product development to garner competitive edges for companies to succeed in the digital economy [119]. In this regard, rich opportunities of design research exist in the strategic domain for smart innovation and value creation [185,186].

(2) Collaborative crowdsourcing of product fulfillment: The emerging human-cyber-physical production systems will provoke changes in many ways for future manufacturing concerning MaaS fulfillment in the factory of the future. Leading experts expect that less basic, repetitive work but more ambitious tasks will be performed in collaboration with the crowdsourcing platform, and thus, the factory of the future will not be deserted, but organized as a network of crowdsourcing platform-driven manufacturing services [187]. Product fulfillment through crowdsourcing has been observed as an emerging trend toward Industry 4.0. It offers new opportunities for reaching external partner's knowledge and resources while allowing companies to focus on their core competencies [143]. The open innovators, open designers, and open manufacturers are all engaged through an inter-organizational network and their crowdsourcing relationships are contractually tied to collaboration for fulfilling different knowledge and capabilities along with a coherent product fulfillment flow [188].

An important issue is regarding the crowdsourcing contracting mechanism [140] which is akin to traditional supply contracting that formally formulates the transactions between the stakeholders to pursue the coordination of diverse decision makers and organize them into supply chain networks [189]. There is a stream of research of negotiation systems for coordination of distributed enterprises, which is consistent with the product fulfillment process [190]. This type of proposing systems entails a bilateral negotiation scheme coincides with a supply contract with an emphasis on the design of efficient negotiation mechanisms, protocols, and strategies [191]. In practice, every organization and entity in the supply chain networks are operating in heterogeneous environments with different objectives and constraints [192]. Since it is observed that a successful crowdsourcing decision-making process requires diversity and independence of the individuals in the crowds [193], the crowdsourcing contracting is more challenging than conventional supply contracting [194], thus lending itself to be an important research area. An interesting exploration opportunity is to design crowdsourcing contracting mechanisms based on new decentralized data management techniques, for example, block chain-based smart contracting [195].

Moreover, any entities involved in the product fulfillment scheme must be considered for their cohort behavior, instead of only their individual operations, in order to achieve the general functionality along the product fulfillment flow and to negotiate with their peers to find compromised solutions [196]. This indicates one important research issue of crowdsourcing contracting with regard to collaborative negotiation along the decision-making flow of product fulfillment [197]. Reference modeling and architecture design are important research questions to be addressed in order to better understand open design and product fulfillment through crowdsourcing [198]. For example, the well-practiced "V" model in systems engineering and formal modeling language like SysML [199] have much potential for streamlining product definition and managing contracting decisions in crowdsourcing of product fulfillment.

(3) Open architecture product and service platform design: Mapping between the customer and functional domains constitutes the front-end issues associated with customization and personalization. Such a planning task usually starts with an existing product portfolio and conforms to those common practices of order configuration and sales force automation. The exploration of soft user requirements involves intensive interactions with customers. Customer co-creation is necessary to elicit latent customer needs. User innovation, data mining, and machine learning lend

themselves to be the main techniques of customer requirement acquisition and reasoning about user experience. Customization and personalization solutions are generated in the physical domain by mapping functional requirements to design parameters based on the shared product and value chain platforms. The fulfillment of hard requirements involves typical decisions regarding product family design and configuration. For personalization of soft characteristics, customer-unique value chains must be designed in such a way that customer participation within a product ecosystem can be separated into a series of value-generating activities.

Usability studies are always useful to design changeable and adaptable workflows that enable customer co-creation and accommodate open innovation. Also of concern are the cost advantages of personalization value chains. Similar to the wisdom of reusing proven design elements, formulating common value chain platforms is deemed to be an effective means to achieve mass production efficiency. New cyber-physical digital platforms offer great potential for implementing value chain platforms into online personalization engines that can provide recommendations on latent customer needs [63]. Integrated design of product and service platforms suggests itself to be of paramount importance for achieving open architecture systems that enable open innovation, open design, and open manufacturing throughout the product realization process, in order to cater to business success in user experience.

The back-end issues associated with open architecture product and service platforms involve the process and logistics domains, which are characterized by process variables and logistics variables, respectively. The mappings from design parameters to processes and to logistics entail process platform design and supply chain platform planning. The main concern of process platform design is to take advantage of existing capabilities and utilize repetitions in production planning. The process view of personalization is enacted as service delivery processes. Identification of changeable, adaptable, and reconfigurable service delivery processes and formulation of service process platforms are deemed to be the fundamental issues of process reuse [200]. Likewise, in the logistics domain, the economic fulfillment of customization and personalization relies on changeable, adaptable and reconfigurable supply and delivery networks.

Furthermore, the social aspect of product and service platforms is emerging as an interesting research area, as a product ecosystem is often associated with social networks. Interactive information sharing among customers is becoming fast and convenient over the Internet with the online social networks or review sections of shopping websites. The increasing availability of data about peer interactions and the popularity of marketing communication techniques based on such interactions have led to even greater interest in understanding the effects of peer influence on customers' choice decisions of product [201]. The extensive reach of the Web and the prevalence of social networking sites have made large amounts of data on social networks easily available, which has recently resulted in their recognition as an important tool for marketing. Because the market is shifting to the online environment and due to the competitive nature of industries, it is important for firms to benefit from such information with appropriate marketing and product line design strategies. A phenomenal trend is emerging toward social commerce [202], which makes academia and industries recall the dot-com and e-commerce revolution of decades ago. Abundant research opportunities exist in response to the emerging trend of open architecture product and service platform development that aims to leverage upon systems, humans, cybernetics, and businesses.

4.3 The System Perspective—Design of Human-Cyber-Physical Systems. *(1) Human-centered cyber-physical work system design:* Industry 4.0 seeks to combine the real and cyber worlds by implementing cyber-physical systems within industrial processes to create a self-managing network between humans, machines, products, and other related objects [203]. Human-centricity is a critical element of digital transformation to Industry 4.0 to allow for a paradigm shift from independent automated and human activities toward a human-automation symbiosis [204]. This symbiosis is characterized by the cooperation between machines and humans in work systems and is designed not to replace the skills and abilities of humans, but rather to co-exist and assist humans in being more efficient and effective [205]. Before the transformation to Industry 4.0, the operator mainly performed physical work. Through the transformation to Industry 4.0, the share of physical work will be replaced by cognitive working tasks in future production systems [206], for example, coordination and organization of materials and other production resources, controlling and monitoring tasks, and decision-making under uncertainties in production [207].

The design of adequate human-system interactions is the focus of the human factors and ergonomics research field [208]. Rich research opportunities exist for new concepts and methodology for designing human-centered mediation processes to involve humans in the system design for Industry 4.0 solutions and to allow the humans involved to express their needs for new Industry 4.0 solutions [209]. It is also important to scrutinize the human role in production before and after the transformation to Industry 4.0 and to address the research question of how and in which ways the transformation to Industry 4.0 changes the role of the operator in production [210]. More research is needed to investigate such questions as: Who and with whom is the operator to interact in a cyber-physical work system? What are the user and system requirements of a smart and skilled operator who performs work aided by machines as needed. This represents a new design and engineering philosophy for adaptive production systems where the focus is on treating automation as a further enhancement of the human's physical, sensorial, and cognitive capabilities by means of human-cyber-physical system integration [14].

Due to changes in required competencies and skills for performing new technical and digital tasks, user and system requirements are changing too for more data privacy, security in automated workplaces, and possibilities for job training. With the aid of the identified tasks and competencies as well as extracted user and system requirements, general design principles can be defined. Several emerging fields such as cobots and digital cognitive assistants have much potential for simplifying the future jobs of operators. In a manufacturing system, operators are faced with complex tasks that require an increasing number of technical and digital skills. Human-centered design is a promising direction for developing assistive systems and workplaces, which minimize the required technical and digital skills of future jobs [211]. Therefore, the involvement of operators with different experience levels and capabilities is crucial for the design process. Workplaces and assistive systems should be easily adaptable according to the operator's roles, experience, skills, and capabilities, as well as the production situation, to provide information, resources, tools, and support needed under specific conditions. In addition to operator engagement and adaptable workplaces, design of human-cyber-physical system must deal with human-data interaction as a new form of human–machine interaction in Industry 4.0.

Moreover, the interaction between human and data is mediated by intelligent objects that constitute a bridge between real (physical) and virtual (digital) dimensions and cover different levels of scale in relation to human, helping at the same time to maintain the contextualization and anchoring data to the sphere of meaning they belong to, i.e., context awareness [212]. A promising area of design research is virtual ergonomics [9], in which digital human modeling technologies [213] are applied to implement a digital mannequin that is driven by the real operator to browse quickly a virtual scene via VR/AR interactions within the workstation while taking real posture during the execution of a work's task. Biometric-based user experience design, especially those based on eye tracking systems, lends itself to be a promising area for investigating human-data interaction in the Industry 4.0 work environment [214].

(2) Design of networked manufacturing systems: Design of adaptive, changeable, and reconfigurable manufacturing systems has

attracted much attention in the past decade [215], owing to its advantages in accommodating customized manufacturing processes that meet the variations in operational requirements or changes of the machine status. If the manufacturing process is to be designed as a superset of all necessary designs to address all possible performance scenarios, then appropriate designs can be selected at reconfiguration time to meet any operational requirements without the need to completely redesign the system from ground up [71]. Digitization of engineering systems in smart manufacturing has resulted in distributed and networked manufacturing systems in a cyber-physical production environment [216].

One challenge for current design methods is how to address variations in product design that are propagated downstream to changes in production scale or variations in product quality necessitated by dynamic changes in the market. The integration of adaptability, operability, and reconfigurability is indispensable for addressing the limitations of the current methods of designing complex networked manufacturing and operations systems. More challenges to be addressed include: Identifying the mechanical and control system drivers and their relations in concurrent design; Building in flexibility in selection and determination of values of design parameters in both systems; Managing the complexity of the design problems; Creation of effective and efficient cloud-based decision support systems; Integration of process and product-related decision models in the comprehensive model-based computational frameworks; Achieving multidisciplinary knowledge exchange between different domains, beyond mechanical and control engineering; and Interfacing domain ontologies necessary for concurrent design as a smart digitalization platform of networked manufacturing systems.

Moreover, an assembly system is a specific instance of networked manufacturing systems within a factory. Assembly system design defines proper configurations and efficient planning strategies to maximize the assembly system performances. Beyond assembly line balancing and scheduling, the assembly system design has to consider the industrial environment in which the system operates [217]. Integrated design of the product, process, and the assembly system is critical in order to utilize the flexibility and capabilities enabled by the Industry 4.0 technologies. Strategic design deals with planning and realizing the potential of interactions between subassembly lines, kitting lines, and the main assembly lines [218]. The operational-level system design needs to explore how new capabilities may affect part routing and scheduling including cases of disruptions and machine failures that have impact on performance in terms of overall flow time and ability to handle a wide variety of end products [219].

(3) Design of cyber-physical production systems for smart and connected supply chains: The design space of production planning and control is extended to a cyber-physical environment in Industry 4.0, in which the tasks of production control are assigned to intelligent objects, such as machines, parts, and products, in order to attain higher flexibility, higher adaptability, and thus a higher logistics performance [220]. The production system behavior depends on the decisions made by intelligent objects with individual and self-contained systems of objectives. This can deteriorate both the stability and the quality of achieved production planning and control solutions. It is important to design future production systems by understanding how to avoid the emergence of myopic behavior, which serves as a basis for creating new control approaches by exploring the design space [221]. The new DE4.0 product development process sheds light on the creation of a structured methodological approach to strategic production planning, which is based on the systematic leveraging of the creativity and experience of a vast diverse network of employees in order to establish an actionable and living integrated manufacturing-driven innovation road mapping process [222].

Focusing on the human role as a key aspect in the use cases for designing process, design thinking methods have the potential to support companies to develop Industry 4.0 use cases of production assessment in the factories [223]. A modular system design approach has good potential for enabling a modular system architecture of configuring system modules for both cyber and physical aspects of the production system [224,225]. Design chain management plays a critical role in examining the relationships between product supply and customer demand in order to distinguish major types of production systems such as a flow line, Toyota production system, job shop, cell, and flexible manufacturing systems, in dealing with the product architecture changes and adopting digital manufacturing technologies like 3D printing [226].

Furthermore, the extended cyber-physical production systems necessitate design for smart and connected supplies [227]. Under the paradigm of Industry 4.0, the present supply chain design policies should model the reverse logistics and examine how product diffusion dynamics in the market affect the economic and environmental performances of an inventory and production planning system [228]. In Industry 4.0, rigid collaboration structures will be increasingly replaced by project-based business partnerships. Such an ad hoc setup of collaborations is needed to deliver solutions uniquely tailored to a customer's needs. Optimal design of agile collaboration networks is an important research area in order to describe the shift in horizontal integration toward a flexibly defined extended enterprise, enabling manufacturers to focus on core competences yet allowing them to offer customized products in any market. In contrast to agile collaboration networks, which build on the horizontal integration of supply chains, vertical integration based on digital technologies allows companies to drive value through transparency and process automation.

Smart and connected supply chains are formed through the vertical supply network by recreating supply flows at a virtual level, allowing the seamless integration and automation of physical processes and providing companies with dramatically increased transparency. It is important to manage the growing complexity of supply chain design while mapping the physical flows continuously on digital platforms. These virtual engineering objects [229] of the supply network's activities are created through cyber-physical systems, such as RFID-tagged raw materials and work pieces. Deployed along the supply chain, they generate data about goods' positions or states in real-time, at multiple levels of aggregation. At the point of the data flows' aggregation, i.e., the supply chain control tower, a maximum level of transparency over the entire supply chain can thus be established through systematic design of smart and connected supply chains [230]. Toward this end, joint product development and supply chain configuration, digital twins for information sharing throughout the supply chain, and coordinated planning of multi-echelon supply chain networks are examples of many research issues worth investigation.

(4) Digital product life cycle and recyclable by design for the circular economy: Design usually assumes that the manufacturing resource is available 100% for the mass production of just one product. Industry 4.0 requires the industry to accommodate disruptions in supply chains and market volatility by producing varying quantities of different products using the same manufacturing infrastructure. Sustainability calls for systematic design over the entire digital product life cycle, requiring that the product quality and per-unit cost be not compromised while maintaining a high level of resource utilization. The digital product life cycle requires designers to anticipate fragmented yet interconnected manufacturing systems that can adapt and morph dynamically in response to disruptions. Product design will have to account for production variations and incorporate smart modular products that can be assembled in a variety of ways. Digital twins of these designs must work in conjunction with the factory infrastructure to produce low volume goods at high quality with mass production efficiency.

Design of digital product life cycle needs to address challenges such as part assembly and disassembly processes must be flexible and allow multiple pathways so that a product can be manufactured in multiple ways using the same process; Consider the nature of supply chain and needs of end users in determining optimal product portfolio for production; Manufacturing processes must be flexible and agile and be able to react to disruptions in supply chain in real-time by modifying either the sequence of manufacturing process or by modifying the product mix and quantities to maintain high infrastructure utilization; and Consider raw materials and product end-of-life criteria to select appropriate materials and processes to build quality products that are environmentally friendly, cost-efficient, and last the designed lifetime.

The emerging circular economy [158] represents a trend of a sustainable industrial system that is restorative or regenerative by intention and design [231]. It replaces the end-of-life concept with restoration, shifts toward using renewable energy, and minimizes the use of toxic chemicals that impair reuse [232]. It aims to limit waste through the superior design of materials, products, systems, and business models [233]. Many times, however, choices made early in the value chain, as in the design stage, hinder the shift toward more circular models and material flows. While eco-efficiency is not a new term in the design world, effectiveness lends itself to be a key circularity principle. However, it has not been adopted as a core design principle to date.

Future research of sustainability design for the circular economy should be geared toward two new unique areas that the make circular economy different from traditional sustainable manufacturing efforts, namely, considering design at the upstream and considering product use at the downstream. New opportunities exist for redesign of manufacturing systems, e.g., co-design of products with end-of-life stakeholders for material recirculation by data-driven inverse analysis of recyclability, circular production pathways by material flow analysis, system dynamics modeling and simulation, as well as circular life cycle value stream mapping and optimization by machine learning of product use and material reuse patterns. Recyclable by design [234] could be a valuable direction for multiscale materials design research [130,235] to design products using materials that are easily upcycled, recycled, or remanufactured [236].

4.4 The Cybernetics Perspective—Design With Smart Sensing and Artificial Intelligence Technologies. *(1) Machine learning and artificial intelligence for data-informed design:* The interests of machine learning and artificial intelligence in engineering design have a long history since 1990s [237,238]. Modern machine learning techniques, such as deep neural networks, are fueling the rapid developments in artificial intelligence [239]. Recent advances in these fields will continue to stimulate this rapidly advancing frontier for novel design theory and methodology that support designers to make better informed decisions.

While the data-driven paradigm sounds appealing and has gained a lot of popularity [81], there are some critical issues or premises deserving scrutiny when considering data-driven design. Data-driven manufacturing is straightforward owing to the availability of a large volume of process data. On the production side, the transport times, position data of the work pieces and the like can be tracked for example by RFID. But what data can be generated and used by product development? There are diverse milestone plans, design data, value stream mapping, but today no high-resolution data, meaning very precise information about the product or the development, is available. In certain indirect areas, the digital reality should be included through various data sources as an essential core of Industry 4.0. There are few systematic approaches for the generation and analysis of high-resolution data for products and product development. As a matter of fact, design is such an engineering domain that is characterized as "knowledge rich yet data sparse," and therefore the seemingly data-driven approaches are not straightforward for design per se [86]. It is thus imperative to examine the theoretical foundation of data-driven design. While embracing big data and analytics, design decision support should emphasize design knowledge management and data value extraction to achieve an integration from data to information and to knowledge in light of the DIKW pyramid model [98].

Various mechanisms and approaches are used in the data-informed design studies for extracting useful knowledge [240]. Relatively few studies have been conducted from the integrated perspective of data-informed inverse design. The systematic frameworks dealing with collaborative aspects of decision makers in integrating related resources used for product design and the environment contexts are still lacking, which is noteworthy for future development. Inverse conceptual design provides a platform for users and firms to communicate the needs and wants to continuously improve design concept directions and evaluation of design for achieving the benefit of inverse thinking and inverse problem solving [241]. Design knowledge discovery and management thus is an important area of research for data-informed design. For example, Lützenberger et al. [242] introduce KbeML as a formal extension of the established SysML standard for a neutral representation of knowledge transfer from product usage information to design requirements. Kim and Ding [243] apply data mining methods to optimal design of engineering systems, in which the fuzzy c-means clustering method is used to organize the design knowledge base with selection rules for design evaluation. To optimize product performance using knowledge and experience gained during in-service, Ibarra et al. [52] demonstrate how in-service knowledge can be captured, fed back, and reused for the design and manufacture stages of the product life cycle. Data-informed inverse design knowledge discovery and learning lends itself to be a valuable research area that enables designers to learn from product in-use performance by informing subsequent designs with product operating knowledge, and consequently improving the through-life product performance.

(2) Dynamic risk management of a cyber-physical sociotechnical system: The DE4.0 arena will be expanded to a cyber-physical world and enacted through a sociotechnical system. The cyber-physical sociotechnical systems (CPSTS) dealt with by DE4.0 will be self-evolving multi-functional systems exposed to new information [244]. The main challenges will be emergent complexity and uncertainty due to the lack of regulations of the free market and its underlying assumptions of perfect and symmetric information, which is inconsistent with reality [15]. A basic research question to be addressed is: What features should CPSTS be designed with in order to dynamically manage complexity and uncertainty through risk mitigation? One possible solution is to design CPSTS to be adaptable to dynamic change where the system will have capability to recognize the risk issue, identify its source and mitigate its effect by readjusting the system to keep operations within prescribed tolerances. Another possibility is to design CPSTS to be relatively insensitive to manufacturing processes under uncertainties. This is related to a rich research area of designing reconfigurable manufacturing systems [215].

The social aspect will become an important aspect of DE4.0. In Industry 4.0, engineering systems are increasingly connected, with complex interactions among social and technical aspects, both during the design process and after fielding. Smart connectivity blurs the boundaries of engineering systems in that their performance is largely determined by how they interact with its ambience or even the society [10]. While traditional Engineering Design has focused on designing an optimal technical artefact, there is an increasing recognition that social and organizational aspects of how designers collaborate and create, and how systems co-evolve with the human and built environments through use, are equally important drivers of value [245]. Sociotechnical system design has emerged as an important research area of design that considers human, social, and organizational factors, as well as technical factors in the design of organizational systems [246]. It is widely acknowledged that adopting a sociotechnical approach to system development leads to systems that are more acceptable to end users and deliver better value to stakeholders. For example, Baxter and Sommerville [247] advocate sociotechnical systems design to be practiced from design methods to systems engineering. The rise of new sources of data and increased availability of artificial intelligence and informatics further creates many opportunities to extend design research into the sociotechnical realm. Many research topics are worthwhile regarding fundamental theories of sociotechnical system design, integrating human behavior into the design process, co-evolution of social and technical systems, and modeling the interactions of systems and organization architecture, along with dynamic risk management for governance of multi-stakeholder systems [183].

(3) Cyber security challenges for DE4.0: DE4.0 entails a human-cyber-physical view of the systems realization ecosystem. Cybersecurity will emerge as an important issue that design research needs to take into account. Existing cybersecurity technology does not work well in terms of scale and dynamics. Existing cybersecurity technologies are based on static networks with reasonable scale (10s to 100s of thousands of nodes in the network). Industry 4.0 will be characterized by very large and dynamic networks. Therefore, cybersecurity research that addresses these characteristics will become an important interdisciplinary research direction for the design community [248]. For example, digital twins with advanced simulation and emulation aims to solve the dilemma between productivity and security through the design, development, and demonstration of a system of systems that embraces the technical, economical, human, and the societal dimensions of future factories [249]. More research questions are related to advanced and novel cybersecurity applications based on Data Science, Artificial Intelligence, and Machine Learning (DSAIM), Automated and Autonomic Response (AAR) to cyber threats, and chaos engineering. Within this collection, AAR will be very important for real-time security of systems, and AAR can be enabled by advancements in the other three components as applied to cybersecurity requirements in DE4.0.

(4) Verification and validation (V&V) of design research: These two issues are always challenging for design research [239]. Systematic V&V are critical in order to assess the accuracy and reliability of the conducted research [250–252]. There has been a significant increase in activity to define V&V methods and procedures [253]. Verification is to determine that “a model implementation accurately represents the developer’s conceptual description of the model and the solution to the model” [254,255]. On the other hand, validation is to determine “the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model” [256,257]. In the context of design research, we posit that “validation is to make sure that the model is doing the right thing, whereas verification is to justify to what extent the model is doing things right” [258]. Similarly to the computational study and algorithm development fields, benchmarking and performance comparisons are the common approaches for design verification. For example, the percentage of improvement in computational efficiency is a popular measure of a proposed design procedure or algorithm. Likewise, performance comparisons of the objective functions using the same data set or numerical example setting indicate to what extent a proposed design optimization model could outperformance other methods for solving the same type of problems.

A particular challenge for design, however, is the validity of a design research in terms of significance of the problem context. For example, human-subject research became prevalent in recent years. Controlled experiments could be conducted by recruiting participants from college students to obtain evidence of statistical tests for verification of a research question regarding design creativity for instance. However, designing a Lego toy versus an aero engine, or by a student designer versus a design expert in the industry, would involve very different problem contexts, leading to difficulties in design validation to convince us that the formulation of the problem context is right. Therefore, formulating a meaningful design research problem that to the largest degree to represent the real world is the key for plausible validation of whatever design research. Field studies, instead of using hypothetical or numerical examples, may be a useful practice to help anchor the specific problem contexts in a close practical relevance to actual industrial applications. While design itself is a more practice-based subject, it is necessary to advance design research in accordance with scientific methods. For example, self-reported data could be enhanced together with objective data using smart intelligence technologies, e.g., neurophysiological measures, in human-subject studies. While empirical and descriptive studies do help acquire practical observations or managerial implications, rich opportunities exist for research on the social aspect of design if taking advantage of more rigorous scientific methods and prescriptive models in the field of social behavioral science, e.g., quantitative social science models, as well as advanced social system models in the field of industrial mathematics, e.g., population dynamics. Furthermore, while the prevailing cybernetics technologies enable tremendous potential for advancing design engineering, the validation of these technologies—to what degree they really enhance design activities—is an important research problem worth scrutiny. The usefulness of whatever high-tech or computer-assisted technologies ultimately is justified by to what extent the original domain problems are solved. This leads to a more complex and important research area of the human-technology frontier as prompted by one of the NSF Big Ideas [179].

4.5 Design Education for the Industry 4.0 Workforce.

Design education of DE4.0 aims at educating strategic engineers—those who have developed the competencies to create value through the realization of complex engineered systems [259]. Digitization is disrupting our world and shaping the challenges that newly minted graduates will need to address in their professional careers. The solution to manage these disruptions is anchored in the principles of sustainability and values that are foundational to mitigating inequities by managing the tensions between the pulls of people, environment, and profit. To succeed in the digitized world, it is important for people in the workforce to continually hone nontechnical, career-sustaining competencies, for example, to continue learning through reflection and the associated creation and articulation of knowledge, to speculate and identify gaps that foster innovation, To ask questions, actively listen, reflect, and identify gaps and opportunities worthy of further investigation, to make decisions using incomplete information, and to think critically (deductive reasoning and inductive speculation) and identify a way forward. It is of strategic importance to promote reflection, dialog and action on modifying curricula to provide our soon to be designers the opportunity to internalize nontechnical career-sustaining competencies and values that empower them to foster societal and technological innovations that promote sustainable development and mitigate societal inequities. For example, upskilling talent in a digitally transforming enterprise becomes critical as a person in a digitally transforming enterprise, in addition to being able to adapt to advances in technology, needs to be able to communicate and relate to people (from different disciplines, cultures, values) who may not be co-located [260,261]. Although people can be trained to use new technologies and how to communicate and relate to other people, it is difficult to teach people how to learn, unlearn what is no longer relevant and relearn that which is needed. Nonetheless, experiential learning has great potential to provide an opportunity for people to learn by reflecting on doing [262]. Through learning, unlearning, and relearning people can recreate themselves, for which generative learning is conducive to enhancing learning with the capacity to innovate and create [263].

There is a discrepancy between workforce qualifications sought by employers and workforce qualification delivered by mainstream education institutions. To alleviate this, more joint efforts between academia and industry are required [264]. *The main challenges in delivering a digitally savvy workforce of tomorrow* are rooted in today’s outdated and inflexible education. Education should prepare students to solve tomorrow`s problem. It should be more focused and intensive, and perhaps degree programs should become shorter so that the knowledge of students will not be outdated by the time they graduate [265]. New means of delivering education online (MOOCs, etc.) are needed as well to increase access and reduce cost of provision at the same time. In addition to the preceding, industrial strategy needs to go beyond the traditional view and baseline of increasing productivity, reducing expenses, and achieving shorter production cycles. Investment into talent and the fostering of creativity, empathy, and cognitive learning of employees may lead to new and innovative business strategies and management philosophies. Another way of addressing the skill gap and attracting more people to manufacturing jobs is to improve the somewhat traditional perception that graduates have of manufacturing, away from being dirty to being high tech and cool. According to the Manufacturer [266], another option might be to embrace diversity, such as hiring more women and other under-represented groups. In general, the adaptation of nontechnical career-sustaining competencies for generative learning is elementary for individuals to become lifelong learners who can upskill or even deskill along with technological change. Nevertheless, in terms of innovation, the need for human–human collaboration will remain important and continue to grow with new knowledge, creativity, critical thinking, and empathy.

The development of a skilled workforce to run the manufacturing enterprises of the future is one of the critical issues that must be addressed in the near term. While Industry 4.0 will usher in economic growth and profitability, there will be loss of blue-collar jobs to the process of automation. Digitization that is powering this transformation has thrown up new challenges not only in the design and implementation of these systems, but also in managing the workforce that keeps these systems operational. While the Industry 4.0 framework can address the requirements for Digitization of the Workplace, the challenges of Digitized Workforce has far reaching impact on the sustainability of the manufacturing process and requires a new paradigm for continuous training of workforce. Some of the issues to be addressed by Digitally Transformed Enterprises are: Identifying the core nontechnical, career-sustaining competencies for success of people in the workforce; How to continually hone nontechnical, career-sustaining competencies of the workforce? Identifying the role of the organization toward it employees and toward society; What constitutes ethical and moral code of conduct for organizations in the era of Industry 4.0? and How does an organization transition from profit-oriented enterprise catering to shareholders' interest to a "learning organization" that is part of a larger "learning society" with the societal interests at its core?

A precursor for students to develop the competencies required by the Industry 4.0 Designers and Engineers of the near tomorrow is to have educators who are savvy in this emerging domain that does not fall into a specific discipline. As a community we are moving on from educating the Engineer and Engineering Educator of 2000 to educating the Engineer and Engineering Educator of "Cybermorrow," for lack of a better term. Industry 4.0 can be considered a meta-discipline of sorts and the role of Design in it is to explore new frontiers and solution spaces in as of yet mostly uncharted territory. The community needs to investigate what it takes to design smart products, smart and interconnected manufacturing systems, smart supply chains, the safe collaboration of robots with humans on assembly lines, the cybersecurity required to make cyber-physical and cyber-human systems safe and trustworthy, especially as they will become increasingly autonomous. How do we design new and disruptive business models of completely new and disruptive technology? One also needs to get used to the idea that Artificial Intelligence, Machine Learning, and Deep Learning eventually will play a serious role in supporting the design of new and innovative products. Efforts toward computational creativity are already on the way, which to many may be a frightening thought, as for decades we as a community have stated that jobs that can be classified as nonroutine and cognitive cannot be replaced by computers. The community also needs to think about the ramifications of a continuing digitization and computerization of the DE4.0 domain. What new policies are required, and how could they be designed? What about the many ethical challenge involved in designing products that operate on data, generate data, and exchange data with other products or systems? What about legal and liability issues in case of damage caused by products or machines that were designed or operated by computers? The message is clear, we need to view the domain of DE4.0 through a whole new lens. To end this section with a down-to-earth example, for decades product development was limited to what manufacturing could do. Today, given all the possibilities of Additive Manufacturing, the pendulum has swung so that now Design is the new bottleneck. As a result, we have already seen "Generative Design" emerge as a new design sub-discipline that is gaining traction. In this sense, our prospect of DE4.0 is indeed a new paradigm rather than incremental change or, even worse, old wine in new bottles.

5 Closing Remarks

The evolution of Engineering Design to DE4.0 in response to the digital transformation powered by Industry 4.0 is reviewed in this paper. Industry 4.0 is based on the principles of decentralization, connectivity, interoperability, information transparency, modularity, and service orientation and is enabled by technologies such as Internet of Things (IoT), big data, machine intelligence, and cloud computing. The foundational principles of Industry 4.0 and the design strategic areas that are necessary for successful implementation of Industry 4.0 are discussed in Sec. 2. In Sec. 3, we cover the key principles of Industry 4.0 and discuss nine strategic areas that provide the positioning framework for DE4.0 in this new era. These areas are indicative of the many emerging issues and opportunities for DE4.0 (see Table 1), and focus on the artefacts, process, or the human aspect of the design to improve overall effectiveness and efficiency of the system realization process, and user satisfaction. However, the growth in these areas is motivated by the needs of respective application domains and does not take a holistic view of the global value chain network of product design, creation, and fulfillment. For example, Engineering Design today considers the creation of digital threads, and digital twins as incidental to the design. Industry 4.0 is still only a set of guiding principles and lacks an architecture or standardization for creation of smart and interconnected products in systems. The creation of these engineered systems must be accompanied by the implementation of management systems that makes it possible to store, share, and use data collected in the field and ensure proper information management throughout the life cycle. Further, this "data-driven analysis approach" is motivated by the belief that knowing how customers use the products can help determine user satisfaction and discover the driving factors for product use, and thereby proactively help companies innovate their product development. This leads to a "chicken and egg" syndrome of how the designer can ascertain the customer's perspective on the use of the product prior to creation of the product. Iterative and incremental designs would work when products have long lifecycles but are not suitable for designing products that are rapidly evolving as technologies advance.

Another example of the shortcoming of Engineering Design is in product creation through strategic engineering. As Engineering Design shifts toward a paradigm of co-creation of product value chain fulfillment by customers in a human-cyber-physical environment, the traditional spectrum of product fulfillment must be expanded to encompass marketing, design, production, as well as the supply and value chains, which in turn must be aligned with the self-adaptability of a learning organization [267]. Further, the creation, production, distribution, trade and consumption of goods in a sharing economy, that is, in a socio-economic system built around the sharing of resources cannot be achieved by simple integration of the technologies in these strategic areas.

Some of these shortcomings are opportunities for research by the DE4.0 community. The state of the art and future directions of this research are highlighted in Sec. 4. Key areas of this research are design for User Experience, Human-Cyber-Physical Systems, Smart Intelligence Technologies, and Strategic Engineering. While the critical areas in the implementation of Industry 4.0 framework were addressed in the research, many of the drivers fueling the transition to Industry 4.0 were not taken into consideration. We argue that successful transition toward Industry 4.0 is not just about the manufacturing factory but requires a new paradigm of design—***Design Engineering 4.0***—that enables reconceptualization of how cyber and physical technologies are seamlessly integrated to identify and meet human needs. It is our view that Design Engineering 4.0 must embody a cyber-physical-human systems view of the systems realization ecosystem (see Fig. 1).

The review and prospects for systems realization under Design Engineering 4.0 presented in this paper lead us to believe that the following drivers and the corresponding challenges must be considered in designing cyber-physical-social systems of the future:

(a) *Internet of Services:* Rapidly changing technologies, customer requirements and preferences, and unpredictable and hard to manage disruptions will drive the future of the DE4.0 ecosystem. An important requirement in this area is the need to customize products to user requirements while producing products of "zero lot size" and "mass production costs." The challenges to be addressed are:
  - How to design products and systems that are resilient, sustainable, and can adapt to changing conditions especially when the change cannot be anticipated at design time?
  - How to develop standards for interfacing and using physical entities and their digital twins across the entire ecosystem from design to product realization?
  - Can digital twins of design variants considered during the parameter selection and optimization phase of the design be used to rapidly respond to disruptions that affect production processes?

(b) *Internet of People:* The distinction between the "physical" and "digital" selves of individuals will get blurred as Industry 4.0 technologies become prevalent. Individuals will play a dual role of co-creators as well as consumers of technologies. Changing user preferences and the way users interact with the products and between themselves will be the main drivers of Design Engineering 4.0. The challenges to be addressed are:
  - How to foster an "Innovation Ecosystem" where consumers and design engineers play a creative role in shaping the systems of the future?
  - How to develop and maintain a workforce that stays in tune with changing technological landscape?

(c) *Internet of Things:* Networked systems and prevalence of IoTs will make data easily accessible throughout the product life cycle. The need to design systems that can collaborate and adapt to improve product quality, process reliability, system agility, and sustainability of the systems realization ecosystem will be the main drivers of Design Engineering 4.0. The challenges to be addressed are:
  - It is anticipated that the information extracted from diverse data streams in real-time will aid decision-making. However, data mining techniques applied to big data are based on the premise that information is encapsulated in the data in some form. Since initial design iterations are based on actual data, is it possible to design systems when partial or no data exist?
  - Can one always build consensus when data streams do not indicate any reliable information or contain conflicting information?
  - Can "Synthetic Data" be created using the digital twins of the processes and used in the early design procees?

(d) *Internet of Commerce:* System design and productization is driven to a large extent by the necessity to make profit. Understanding the interactions between businesses (B2B), business and consumers (B2C), and between consumers (C2C) is necessary to identify all the avenues for monetizing products and services in the age of Design Engineering 4.0. The challenges to be addressed are
  - How can design anticipate the many ways in which the product can be monetized?
  - As a result of networked systems and ubiquitous design and data sharing, Cyberthreats are no longer restricted to loss of privacy or the financial domain. Cyberattacks can cause everything from degradation of product quality to complete lockdown of system realization ecosystem. One of the most urgent challenges is how can designers inoculate systems against threats when the nature of interaction between system components is unclear at design time?

The amalgamation of these four drivers is the essence of Human-Cyber-Physical Systems. The key attribute of these systems is the shared autonomy between cyber systems and humans. Often, it is the purview of the designer to select the transfer of autonomy from cyber-operators to human operators and vice versa. Often the decision on when a "Human supports a Computer" or when a "Computer supports a Human" is a variable one that changes as the system evolves in time. This leads to the concept of evolving Human-Cyber-Physical-Social Systems.

> James Kip Finch, the noted American engineer and author remarked that the "engineer has been, and is, a maker of history."

This has never been more relevant! Design Engineering 4.0 is foundational to the creation of these organic systems that will play a major role in shaping our lives over the next few decades!

Acknowledgment

Roger Jiao gratefully acknowledges the support of the Renewable Bioproducts Institute at Georgia Tech, the GT Quantum Alliance, and the National Science Foundation NSF Future of Work at the Human-Technology Frontier Big Idea under Grant No. 1928313. Janet K. Allen gratefully acknowledges the John and Mary Moore Chair at the University of Oklahoma. Farrokh Mistree gratefully acknowledges the L.A. Comp Chair at the University of Oklahoma.

Conflict of Interest

There are no conflicts of interest.

Appendix – Glossary

Cybernetics	Cybernetics is the science of "systems thinking" and deals with concepts such as control, communication, learning, cognition, adaptation, emergence, and efficiency that are necessary for understanding complex systems [1].
Design Engineering 4.0 (DE4.0)	Design Engineering for Industry 4.0 (DE4.0) represents the "human-cyber-physical view of the systems realization ecosystem" that is necessary to accommodate the drivers of Industry 4.0 (IoX) and provide an open ecosystem for the realization of complex systems. Seamless integration of digital threads and digital twins throughout the product design, development, and fulfillment life cycle; ability to accommodate diverse and rapidly changing technologies; mechanisms to facilitate the creation of new opportunities for the design of products, processes, services, and systems are some of the desired characteristics of DE4.0.
Engineering Design	Engineering Design is the process of devising a system, component, or process to meet desired needs. It is a

Continued

	decision-making process (often iterative), in which the basic science and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation.
Digital Thread	Digital Thread is a digital communication framework that enables the streamlining of design, manufacturing, and operational processes to efficiently design, build, and maintain engineering products. It represents a data-driven architecture that links together information generated from across the product life cycle.
Digital Twin	The digital twin refers to a digital model of physical entities in a cyber-physical system. In a manufacturing context, a digital twin encapsulates design specifications and engineering models that are used to describe the geometry, materials, components, and behavior associated with a physical entity. It also includes the as-built and operational data unique to the specific physical asset that it represents.
Global Value Chain Networks	The global network of suppliers, manufacturers, customers (internal and external), regulators, policy makers, etc.
Human-Cyber-Physical	HCPS is a natural extension of CPS that adds the consideration of human interactions and cooperation with cyber systems and physical systems, supported by ICT [2].
Industry 4.0	The comprehensive transformation of the whole sphere of industrial production through the merging of digital technology and the internet with conventional industry. [3]
Innovation in the context of Design Engineering 4.0	Is based on or makes use of Industry 4.0 principles to enable or realize new and innovative products or product-service systems.
Intelligent Design Automation	Design automation is a knowledge-based engineering approach which logically combines various engineering concepts with real-time application study during product development.[a]
Internet of Commerce	Internet of Commerce refers to the buying and selling of goods or services over the internet, and the financial transactions and data exchange required to complete the process. Transactions can be characterized as Business-to-Business (B2B), Business-to-Consumer (B2C), or Consumer-to-Consumer (C2C).
Internet of People	Refers to the digitalization of relationships between people and the collection, processing and application of personal data. It forms a network of collective intelligence and stimulates interactive communication among our digital selves through digital devices, the Internet, and sharing of data.
Internet of Services	The term Internet of Services arose from the convergence of two concepts: Web 2.0 and Service-oriented architecture (SOA) with the primary goal of creating new services using existing online resources. Web 2.0 is characterized by four aspects: interactivity, social networks, tagging, and web services. SOA is a way of designing and building a set of Information Technology applications where application components and Web Services make their functions available on the same access channel for mutual use [4].
Internet of Things	The Internet of things (IoT) is described as the network of physical objects—"things" or objects—that are embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the Internet.
IoX	IoX is the collection of internet technologies, namely Internet of Things, Internet of Services, Internet of Commerce, and Internet of People.
Open innovation in the context of Design 4.0	An expansion of the original Open Engineering paradigm/process that embodies one or more of the social product development tenants.
Platform to support DE4.0.	A cloud-based digital platform that supports servitization of the product realization process through open design and open manufacturing.
Servitization	The shift from creating (designing) products to creating (designing) cyber-physical or cyber-social product-service systems.
Sharing Economy	The sharing economy is a socio-economic system built around the sharing of resources [5]. Its application includes the shared creation, production, distribution, trade and consumption of goods and services by different people and organizations [6].
Smart X: Smart Internet of Things, People, Services, etc.	Smart X refers to the network of entities (things, people, and services) embedded with sensors, software, and other technologies to facilitate data exchange and enable intelligent decisions and to perform services.
Social product development	Social product development (SPD) is defined as a group of "coalescing tools and socio-technologies" represented by several tenants including crowdsourcing, internet-based mass collaboration, open innovation, and cloud-based design and manufacture. It is based on networked collaboration in design teams, lading to shorter lead times, and significant reductions in R&D costs. SPD supports the democratization of Design and Innovation across society (beyond the expert domain) [7].

[a] https://blog.rgbsi.com/cad-customization-design-automation

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