Interpreting the industry 4.0 future: technology, business, society and people

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A holistic view of the fourth industrial revolution

The steam engine became a symbol for the transition from manual to mechanical labor and thereby the key technology of the first industrial revolution. Since that time, two industrial revolutions have followed, namely, mass production enabled by electric power and automation advancements enabled by information technology. Now, a fourth industrial revolution, called Industry 4.0 or I4.0, has been envisioned: the merging of the physical and digital worlds by means of cyber-physical systems and autonomous machine-to-machine communication.

Expectations for I4.0 are high. For instance, the Fraunhofer Society expects a cumulatively added value potential of 23% between 2013 and 2025 (Bauer *et al.*, 2014). Similar to industry, which has paid attention to I4.0, academia regard I4.0 as a key research topic. Since 2012, the number of publications on I4.0 has rapidly increased each consecutive year. A similar trend is observed for terms related to I4.0 (smart industry, smart manufacturing, industrial internet and cyber-physical systems).

Despite the increasingly important role of I4.0, however, firms tend to lack knowledge about how to determine how I4.0 would affect their business and how to benefit from it. While the literature has attempted to understand I4.0, typically it has considered a very domain-specific angle, discussing only particular aspects of this revolution. However, if this is a revolution, it is not very likely to be a phenomenon affecting only specific aspects of business and society. Instead, revolutions are holistic phenomena. They not only affect technological developments and business models but also may have profound societal implications for people's education and work.

To understand the current development and be able to take advantage of (rather than be a victim of) the next industrial revolution, it is necessary to illuminate this trend from different angles. Such massive shifts imply changes in the paradigm (Kuhn, 1970): the organizing principle and fundamental assumptions accepted by all in and those linked to industry. Once the paradigm shifts, industries and their actors need to reorient, rethink or even reinvent themselves.

Given that innovations and shifts do not take place in a vacuum but are "part of larger processes and are entangled with organizations, other technologies, sector dynamics and anticipations of and responses from, society" (Rip, 2012, p. 158), a multilevel perspective can be most useful to examine how the context of innovation and shifts affect the dynamics of organizations (Rip, 2012). Using a multilevel perspective approach means placing the industry in a context that goes beyond considering purely economic aspects. In this approach, the political, technological and material dimensions of innovation, as well as relevant social and cultural aspects are integrated.

This paper takes a holistic perspective of I4.0 and analyzes its technological core, business implications, societal requirements and people challenges, as well as the interactions among these subdomains, which jointly form the I4.0. To this end, we developed the following questions:

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Q1. Which technologies have the potential to be pacemaker technologies for the I4.0?

Q2. Which changes in business models is I4.0 inducing?

Q3. Which societal systems have to change to enable I4.0?

Q4. What effects could I4.0 have on work and education?

Conclusive answers to these questions can be presented only in hindsight. However, a holistic I4.0 model could try to create some scenarios. No such model can be found in the literature thus far. Hence, this paper provides a series of building blocks that jointly can be used as a tool for analysis and scenario building. At the end of this paper, we summarize the findings in the form of a checklist that organizations can use to individually discuss the implications and chances of I4.0 for them.

We report the results of a joint attempt by 50 professors of the University of Twente, The Netherlands, and industry practitioners, who gathered in two physical world cafés to develop hypotheses regarding I4.0. Reflecting on the cross-functional approach preferred by the University of Twente, we brought together scholars from a multitude of disciplines to provide a differentiated and realistic picture of the developments of this complex phenomenon by taking a holistic view.

In the next section, we explore I4.0 and take a holistic look at its characteristics. Subsequent chapters then report the results of our research on the technological, business, society and human aspects of I4.0. Based on these insights, we present a model and draw conclusions and managerial implications.

Smart industries: technological innovations turning into industrial revolutions

Industry has undergone many developments, smaller modifications and greater transformations. Some more paradigmatic changes have been called industrial revolutions. Several industrial revolutions have taken place (Kagermann *et al*., 2013). Authors usually agree that industrial revolutions are technology-induced but lead to and require fundamental economic and societal changes (Brynjolfsson and Hitt, 2000; Perez, 2010). Evangelista and Vezzani (2010) empirically show how firms become successful when they implement technological and organizational changes at the same time.

The first industrial revolution replaced craft production through central factory production and used water and steam power for mechanized production. The second industrial revolution depended on the electrical motor, which allowed for highly standardized mass production. What is called the third industrial revolution was driven by robotization and digitalization, leading to a new level of automated repetitive production with new products and markets. We now refer to “smart industries” resulting from I4.0 as the erosion of boundaries between the physical and digital worlds, between the industrial production space and other infrastructures, systems, organizations, processes and people. There is a vast and complex digital ecosystem for industrial activity emerging beyond classical value chains and mere information flows. Cyber-physical production systems and globally interconnected value chains, the smart inclusion of users and new kinds of products seem to extend our expectations regarding what industry is and can do. Distinguishing from the third industrial revolution (digitalization and roboticization), the fourth can be described as comprising the following elements: cyber-physical systems characterized by autonomy and machine-to-machine communication (Schiele and Torn, 2020).

The most recent concept of industrial change even considers a potential next industrial revolution, which would then be Industry 5.0 (I5.0). Observers state the need for a “human touch revolution” that integrates human and artificial intelligence (AI) instead of making humans obsolete for digitized industrial production (Nahavandi, 2019). Again, in an ongoing process, for a subsequent industrial revolution, new pacemaker technologies would have to emerge, with new business models, societal changes and human implications.

Method: a series of world cafés with experts

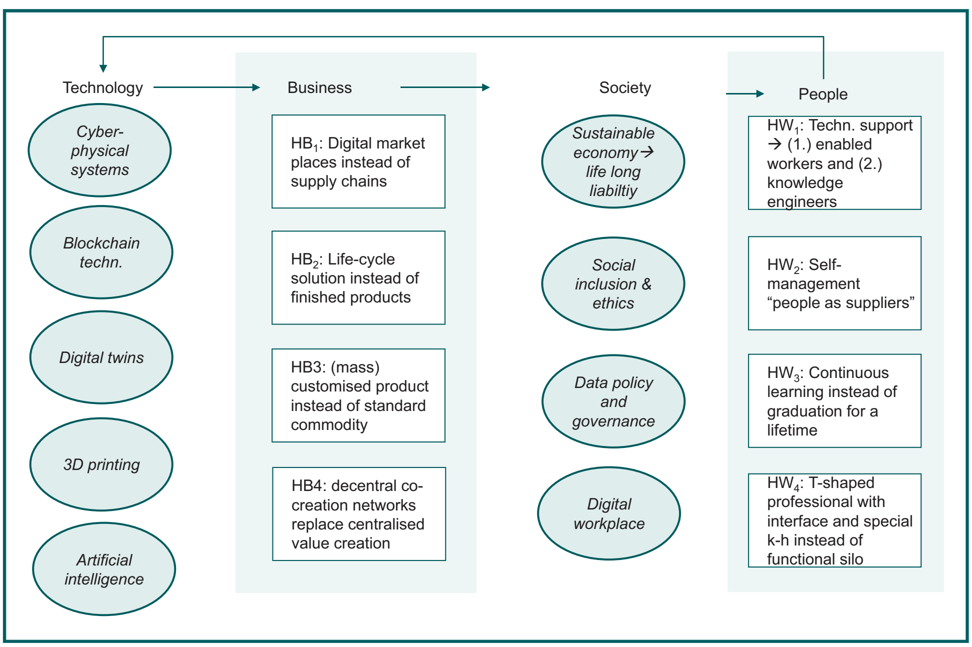
I4.0 is a recent and ongoing development. Trying to understand it and propose guidelines for handling the change can be done either deductive based on theoretical considerations, in abductive by designing new applications or inductive by assembling a series of observations. Taking into consideration that an industrial revolution may best be described as a multifaceted event, no single theory would be likely to provide a holistic picture. Therefore, we decided to gather observations from different angles and assemble them into one model. We chose a special form of focus group study, the academic world café (Goldberg and Schiele, 2018).

In a world café, the participants divide themselves into small groups that come together at different tables. At each table, one aspect of the research problem is discussed; in the case of an academic world café, a moderator hosts the debate. After a predefined period of time (usually 20–45 min), the participants are asked to change tables. At the beginning of each round, the moderator summarizes the previous discussion points and then identifies a new point. This process is repeated until each participant has contributed to every discussion topic. The final step is an evaluation round in which the participants rate the aspects at each table with the help of "stickers." In doing so, a ranking of the aspects emerges at each table. As such, the world café setting allows researchers to access all participants' knowledge but avoids overemphasizing individual opinions, thereby creating more realistic outcomes.

In the present case, we conducted two world cafés. The first brought together 35 professors from technical, business and social sciences working on I4.0 topics at Twente University. The results from this workshop were used as input for the second, validating workshop that gathered an additional 15 business representatives. In each case, the participants grouped at four tables (technology, business, society and people) and afterward identified the findings they considered to be most important.

The following Figure 1 gives an overview of the I4.0 model that emerged from the analysis. Five potential pacemaker technologies are expected to provide several deep

Figure 1 Twente smart industry 4.0 vision



changes in business. At the same time, some of the social subsystems of our society, such as the legal system, are likely to be strongly affected or have to support the revolution to take place. Finally, we discussed the impact on people and their education, which are pivotal to ensure that society can seize the technology-induced opportunities I4.0 is offering, all of which are captured in the “Twente I4.0 model.” While all these elements together are expected to coin the fourth industrial revolution, not all of them are likely to have the same impact on each organization. For instance, not all technologies will be directly applicable in each situation. Therefore, below we distinguish between several building blocks. We suggest that firms may want to use these building blocks as input for developing scenarios through an individualized discussion on I4.0’s impact and chances for their particular situation.

Subsystem 1 – Technology: digital twins, blockchains and three-dimensional printing connected in a cyber-physical world

The following section describes five technologies considered to be the most likely to shape I4.0: cyber-physical systems, digital twins, blockchain technology, three-dimensional printing and AI (further suggestions in the world café evolved around technologies such as “cobots,” i.e. collaborative robots, biologization/exocortexes and battery energy). The development of each of these technologies that received a large number of votes in the world café has been disruptive in recent years, and applications for all of them are expected to increase rapidly in years to come. Moreover, these technologies are not fully independent of each other, and it is to be expected that I4.0 applications will use a combination of them.

Cyber-physical systems are feedback systems that detect and analyze changes in the environment based on data retrieved from sensors, with the aim of making autonomous decisions that impact entities in the real world, in this way linking the physical with the digital world. Cyber-physical systems build upon the development of embedded systems and are characterized by a strong integration of collaborating sensors, actuators and software.

Digital twins are computer-aided design models that represent accurate copies of physical entities in real-time. Digital twins enable companies to assess the consequences of product, process and servicing decisions by using virtual models. Hence, digital twins can contribute to significant cost savings during product development (testing) and maintenance and can also be used to establish a permanent and ongoing link between producer and product.

lockchain is a distributed database comparable to an electronic ledger that can hold any type of information (such as transactions, records or events). A blockchain consists of chained blocks and continuously grows every time a new block of information is added (i.e. linked to the preceding blocks). Unlike existing transaction networks, blockchain does not need a single centralized authority due to the internal validation of changes. Instead, the ledger is maintained by a set of computers that each hold a full copy of the database. This part of the network validates each transaction based on a predetermined set of rules used to validate transactions and to ensure that changes to the blockchain are correctly implemented.

Three-dimensional printing, also referred to as additive layer manufacturing, has been around for 30 years but has only recently evolved from a set of promising tools in the lab to disruptive technology. The rapid rise of three-dimensional printing is not a singular development, as technological developments that improved the capabilities of both materials and printers and market factors, such as the increased need for shorter product development cycles and a growing demand for customized and personalized products, played a part in realizing this growth.

AI and machine learning, again, are not new. However, only now, due to the availability of very large volumes of data and processing capacity, AI is becoming increasingly critical to develop techniques that can cope with such volumes while extracting knowledge from data in (quasi) real-time and using it to improve the execution and planning of future and in-progress business processes. While the service and technology literature seems to emphasize the benefits of using AI, the economic literature tends to focus on threats to human jobs. In a similar way, instead of exploring how businesses can benefit from people working alongside AI, most attention in the literature seems to be aimed toward how AI will replace humans. Nonetheless, integrating the distinctive capabilities of both humans and AI is expected to enhance decision-making (Jarrahi, 2018).

Summarizing, the following technologies are expected to be the building blocks and shape the fourth industrial revolution. They could also serve as starting points for an organization-specific discussion:

Technology building blocks: As pacemaker technologies igniting the fourth industrial revolution, one or more of the following technologies are likely to play a pivotal role, namely, cyber-physical systems, digital twins, blockchains, three-dimensional printing and AI.

History shows that the advent of certain technologies alone did not lead to an industrial revolution. This only happened once a business model was found that benefited from those technologies and provided means for their further development. Therefore, the next section will discuss possible business scenarios.

Subsystem 2 – Business: from closed supply chains to electronic marketplaces

To create a whole picture, we go from considering upcoming technologies to business implications. Depending on the demand, autonomously negotiating systems can flexibly reconfigure supply systems (Schulze-Horn *et al.*, 2020). Therefore, a more open, marketplace-like, value-creating system can replace inflexible closely tied chains. As a consequence, focused competence-based models replace supply chain integrated business models. This combination could revitalize the idea of electronic marketplaces, which failed during the “dot.com hype” in the early 2000s, presumably because as long as a human-machine interface is required for entering demand into the system, an electronic marketplace could not offer much more than a more comfortable paper catalog with invoicing function (Schiele and Torn, 2020). However, if demand is generated automatically and cyber-negotiation takes place, then e-markets could have a new role, fulfilling promises made in the early 2000s, when the expectation was that e-marketplaces would become dominant. Based on this logic, we suggest the following:

Business building block 1: I4.0 can dissolve classical integrated supply chains and replace them with flexibly reconfigured electronic marketplaces as transparency increases and transaction costs diminish.

By further extending the idea of digital twins, the second technology addressed, one consequence becomes apparent: in an interconnected world, there is no such thing as a finished product. Throughout its entire physical life, the product can have a digital twin, as a digital representation of a physical system connected through sensors. First, the twinning technology allows changing the product based on collected and then simulated information. Second, an interaction between both the digital and physical twins can take place. For example, imagine a navigation system in a car that constantly updates instead of being static and based on a one-time data medium.

Business building block 2: Rather than selling a finished product, a solution to a problem is sold, which may be updated during the component's use, creating life-cycle solutions.

A life-cycle perspective has fundamental implications for business models, namely, long-lasting relations are needed, new types of contracts have to be developed and liabilities change (Schuh *et al.*, 2014). Nevertheless, this perspective considers not only the time-related aspects of a product but also the way it is produced and how it looks. We are talking about "smart products," which continuously interact with other products, as well as their producers and users. These products require a suitable production method, where especially the individuality of the final product is challenging. Here, three-dimensional printing technology could be the key to more individualized products.

Business building block 3: Because of the easy reconfiguration of production and technologies of end-user involvement, mass customized production becomes the rule rather than the exception.

A core feature made possible by new I4.0 technologies, such as the transparency made possible by blockchains, is the decentralization of business activities. Transactions overseen through central coordination within a firm can be replaced by technology, thus reducing transaction costs (Brynjolfsson and Hitt, 2000). Hence, the organizational model can also change, with a multitude of decentral actors coordinating themselves in cocreation networks, leading to the scenario building block:

Business building block 4: Decentral cocreation networks replace centralized value creation.

In conclusion, the business implications of flexible, decentralized and small quantity production and emerging technologies are compelling and support the dissolution of classical chains. For instance, new intermediaries can be established that are specialized in three-dimensional printing of all kinds that will allow for shipping only plans and a few raw materials around the globe instead of manufactured components. This could be a technologically-based motor for the deglobalization of supply chains. Products are produced in a decentralized way; here, the product is printed, close to and interacting with the end user. Even more, the team play between the digital twin and the three-dimensional technology aligns the digital and the physical world, creating life-cycle solutions.

Changed business models change society, and in some cases, societal frame settings must occur before some business changes. Hence, the next section summarizes the discussion on our findings on how I4.0 is embedded in society.

Subsystem 3 – Society: sustainability, digital learning, data governance and social integration

At a more general level than technology and business, I4.0 is embedded in the broad social context. Critics affirm that the I4.0 model would not pay enough attention to issues regarding sustainability (Nahavandi, 2019). On the other hand, the technology required for sustainability is emerging in I4.0. For instance, transparency created through blockchains and digital twins strongly promotes the enforcement of environmental regulations throughout the supply chain. A digital twin cannot be dumped anymore! Because of I4.0 transparency enhancing technologies, value chains can become value circles, and thus, resources can be further processed instead of being thrown away, value creation can be increased and broadened. Hence, we posit the following:

Societal building block 1: Supported by I4.0 technologies, a sustainable economy can evolve into a circular economy as a basic principle of doing business.

Data and monitoring-intensive smart industrial practices, often accompanied by artificial forms of intelligence, present opportunities and challenges for those whose data are used and those who use their data. To ensure legal, responsible and secure data handling, the relevant rules and policies will need to be extensively adapted. These will affect the human-machine interaction, and even more, as a typical element of I4.0, the machine-to-machine communication. For instance, the legal system has to adapt so that cyber-negotiations among machines become possible.

The circular economy also includes the invention of and experimentation with governance that provides order for the new smart data world (Kuhlmann *et al.*, 2019). In addition, digitalization changes public governance, while smart governance emerges only when there is a large amount of experimentation. Smart industry needs a framework of smart governance. Both public administration and governance, as well as private business and corporate governance, may be using mutual adaptation processes, learning from each other and in competition to develop a better and more accepted approach to smart governance.

Societal building block 2: Changes in the technological infrastructure and economy will lead to innovation in governance, including novel legal requirements.

The great sociotechnical transformation of smart industries could entail both the inclusion and exclusion of people, industries, knowledge and geographical regions; society could be divided either more or less. It is not yet clear how much I4.0 would increase or decrease inclusiveness, justice, solidarity or responsibility, which is an ethical issue. A continuum will exist between simply harvesting data (smart industry as extracting industry) and total surveillance (transparency through I4.0 technologies as a basis for total authority – the "Chinese model"). People and companies will increasingly access a wide range of information and data; at the same time, an increasing number of people's lives will be captured as data. The big data industry could make both people and smaller companies dependent and supplicants who cannot easily afford every data service or knowledge development (Moore and Tambini, 2018).

Societal building block 3: Because of integration, data-driven processes can divide and unite.

If smart technology plays a more pervasive role, it will have the potential to change work. There are two sides to this story, namely, on the one hand, the cyber-physical system (including AI and robots) has to learn to respond to human needs and act to work together. Second, people have to learn to work with intelligent machines, for very specific work processes, to program machine processes before any work can be done and in management, for instance, with a Chief Robotics Officer (Nahavandi, 2019) or a Chief AI Officer.

Societal building block 4: The digitization of workplaces opens up intersections of learning for living, working and doing business.

Subsystem 4 – People: technology-enabled workers and knowledge engineers

In this part, we identify a number of implications of I4.0 for individuals – i.e. workers and their occupations and the details of the new "digital workplace." Technological developments change how blue-collar workers perform routine jobs and white-collar employees in knowledge industries (e.g. banking and law firms). Because of changes in the nature of jobs, employees are being enhanced with robotics, AI, virtual reality, sensors and software. For example, the jobs of operational workers are becoming enabled by technologies that support their work, and engineers will organize and interpret the information provided by technologies and use their expertize to design new systems and tools. We call individuals in the first job group "enabled workers" and those in the second "knowledge engineers." Technology-enabled developments bring the promise of higher productivity. Enabled workers can use virtual reality glasses or robot arms to guide them through the physical manipulation needed to execute their work.

Many traditional engineering activities and even aspects of decision-making in organizations may be better executed by AI systems with more calculation power than any team of humans. Knowledge engineers need to organize the AI tasks that need to be executed, interpret the information and define the requirements and interface with customers. Thus, knowledge engineers become strategic decision-makers and flexible problem-solvers.

People building block 1: I4.0 technologies allow operational employees to become enabled workers and strategic employees to become knowledge engineers.

To operate in a flexible way, organizations increasingly make use of "gig workers," talent platforms and contractors for project work to offer short-term offline contracts and freelance work to independent workers, each person becoming a supplier. The emergence of the gig economy is reshaping the traditional employer-employee relationship as more contractors and freelancers fill roles once reserved for workers having more permanent jobs (Graham *et al.*, 2017).

At the same time, organizations choose to structure work based on self-management (Bondarouk *et al.*, 2018). First, cyber-physical systems autonomously allow for monitoring and controlling individuals. Second, as objects and people become more interconnected and information from various sources becomes more transparent, individuals at the operational level can use different information sources at the same time. Both trends suggest that individuals will become empowered to take responsibility and take on decision-making authority based on the data.

People building block 2: I4.0 technologies offer opportunities for a gig economy where workers become suppliers or freelancers and more empowered, which will lead to the development of self-management in organizations.

This shift can cause skill-based training systems and aligning skill sets to lag the real time requirements. Because of the accelerating speed of innovation, a continual (say life-long) learning approach will be required for workers to remain productive. In the I4.0 context, mainly individual employees will take responsibility for updating their own skill sets to stay employable. Therefore, employees will need continual retraining through novel forms of virtual and modular education. For instance, workers may follow and combine short-term modules from different knowledge providers to earn micro-certificates – with courses offered through platforms and online providers. As a consequence, knowledge marketplaces may emerge, replacing fixed curricular educational chains.

People building block 3: I4.0 technologies require new competences and skills that employees need to develop through continual learning using virtual, online and modular educational platforms to stay employable.

As employees closely interact in changing constellations with other employees in a gig economy, they need to have a fair understanding of the activities of their peers. It will no longer be sufficient to master just one competence and embed it in a coordinating hierarchy. Instead, the new I4.0 economy may require boundary-crossing competences. The breadth and depth of skills that employees will need in I4.0 is illustrated by what is often referred to as the T-shaped professional (Leonard-Barton, 1996). The vertical bar of the T represents a person's deep understanding of one subject matter and an industry. The horizontal stroke of the T refers to the ability to work across a variety of complex subject areas with ease and confidence, which leads us to post the following:

People building block 4: I4.0 technologies require T-shaped professionals with boundary-crossing competences that combine soft and technical skills who need to be recruited, developed, rewarded and retained with technology-enabled human resources management practices.

Eventually, these employees, then, are equipped to further develop the technical solutions and business models needed to fulfill the I4.0, and a self-reinforcing cycle emerges.

Conclusion: a reference list for organizations preparing for I4.0

This paper reports on a joint effort to develop a holistic picture of I4.0 and identify potential pacemaker technologies, business opportunities, societal challenges and people requirements related to this revolution. In terms of managerial actions, we propose that organizations may profit from systematically analyzing all four elements of the I4.0, as well as opportunities and challenges. Such a procedure entails a four-step approach reflecting the four elements. Each of the four elements and the importance of their respective building blocks for the particular case is discussed in detail by a targeted working group, but it is important to bring all elements together and try to connect them in an iterative way considering the particular situation of the organization. In the end, these findings could be used as input for I4.0 scenarios leading to a roadmap for the organization where each of the dimensions represents one layer of the roadmap.

First step: What are the implications of the five technologies for the organization? Are there processes that could benefit from the automatic detection of changes through sensors? Would the supply chain or the production processes benefit from being embedded in a transparent blockchain? Does the organization make products that could be followed through their lifecycle by implementing a digital twin? For physical products and components, could three-dimensional printing lead to better and/or cheaper parts? Finally, are mass data available that could be analyzed by AI and would this have benefits?

Second step: What implications do business cases have for I4.0 technologies (and, the other way around, which technologies will be needed to enable new business models)? The first hypotheses related to electronic markets focus on different product presentations and may fundamentally change buyer-supplier relations. Can products/services be sold and bought via algorithms? Are there implications for life-cycle products? If we can use twinning technology, for instance, it could become possible to link to a product throughout its life and sell addenda and maintenance parts, thereby eliminating intermediaries. Is the company becoming an intermediary? In the latter case, developing options for integration could be a way forward. Can the organization mass customize and produce lot size to add value? Finally, does new technology such as AI enable new forms of collaboration, making current connectors superfluous? To answer these questions, firms must have both a good understanding of the technologies and of their own value-creating model (Slywotzky *et al.*, 1997).

Third step: What are the societal implications/constraints/requirements of a technology-induced change in the business model? It is worth taking a broad perspective here, as it could well be that social inclusion issues may prevent novel business models from being implemented. Likewise, data privacy issues may require legislative action before new business models arise, such as those propelled by machine-to-machine negotiation. Life-cycle products, in turn, offer a great opportunity to implement new sustainability standards. If societal requirements are especially pronounced in the industry at hand, this may be the starting point of changing the business model and looking for I4.0 technologies supportive of this change.

Fourth step: Taking all these changes into account, a thorough analysis of the requirements and changes needed at the work level can follow, and training programs can begin. Can we distinguish between technology-enabled workers and knowledge engineers? Are there organizational models for stronger self-management? Does the workforce possess sufficient "T-shaped" talent to fill knowledge gaps?

In the end, the Twente I4.0 model (Illustration 1) can be applied as a four-step discussion scheme and used to structure individual discussions on how to prepare and profit from the opportunities I4.0 offers. Nobody can predict the future, but the scenario building blocks developed here can help to derive scenarios, which serve as input for the individual discussion and eventually derivation of an I4.0 roadmap.

We emphasize that in the previous industrial revolutions, only the combination of new technologies with a fruitful business model, embedded in a supportive change in the social and people systems, rather than many purely technical models, made the revolution possible and raised mankind to higher levels of prosperity and freedom. This is our current challenge: to identify the economic model that takes advantage of new technologies and embed them in society. It may turn out that many of the issues raised in this paper, such as the coincidence of technical and socio-economical changes, will also be addressed in I5.0 concepts; while, as for now, many actors are still struggling to cope with the challenges of I4.0 – or even implementing the last technologies of I3.0, as the basis for then embarking in the 4.0 journey.

Keywords:
Business models,
Technology,
Strategic management

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