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The Fourth Industrial Revolution (Industry 4.0): Technologies Disruption on Operations and Supply Chain Management

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Position Paper

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1. Context

During the last five years, journals in robotics, electronics, computer science, and production engineering have devoted significant attention to Industry 4.0 and related subjects, including additive manufacturing/3D printing, intelligent manufacturing, and big data (Lee et al., 2014; Xi et al., 2015; Pfeiffer et al., 2016; Mosterman and Zander, 2016; Chen and Zhang, 2015; Jia et al., 2016). A systematic literature review on Industry 4.0 or on some of its specific technologies (e.g., additive manufacturing) is provided by Liao et al. (2017), Strozzi et al. (2017), and Niaki and Nonino (2017) among others. Although prominent scholars have acknowledged the relevance of Industry 4.0 for management in general, as well as for Operations and Production Management (O&PM) specifically (Brennan et al., 2015; Fawcett and Waller, 2014; Holmström and Romme, 2012; Melnyk et al., 2018), relatively little consideration has been given to these topics by mainstream O&PM journals, especially on Industry 4.0 technologies' disruption on operations and supply chain management. A few prominent exceptions are represented by the recent attempts to shed lights on (a) the link between Industry 4.0 and lean manufacturing (Bruer et al., 2018; Tortorella and Fettermann, 2018); (b) the link between internet of things and supply chain management (Ben-Daya et al., 2017); (c) the impact of additive manufacturing on supply chain processes and performances (Liu et al., 2014; Oettmeier and Hofmann, 2016; Li et al., 2017); (d) the short-term supply chain scheduling in smart factories (Ivanov et al., 2016).

While in the past there were very few pilot Industry 4.0 projects, the number of applications has significantly increased, both in terms of demonstration and "real" factories hence give rise to more empirical studies. Demonstration factories include Factory 2050 at the University of Sheffield (UK), Demonstration Factory at Aachen University (Germany), TRUMPF Group Factory in Chicago (USA), and SmartFactoryKL in Kaiserslautern (Germany), whilst "real" factories are at Audi's Ingolstadt factory (Core77, 2016), Arla Foods (ARC, 2016), Siemens' Amberg plant

(Siemens, 2016), and Bosch's Feuerbach plant in Stuttgart (Automotive World, 2016). A recent survey conducted by PwC on more than 2,000 companies from 26 countries showed an overall adoption rate of Industry 4.0 concepts (e.g., digitization and integration) of 33%, and forecasted that it will reach 72% by 2020 (PwC, 2015). This growth will be further fostered by the funding and innovation plans launched by several countries leading this industrial revolution, e.g., Manufacturing USA in the United States, Industrie du Futur in France, Industrie 4.0 in Germany, Industria 4.0 in Italy, Made in China 2025, Made Smarter UK. It is argued that different industrial sectors have different pace of adopting Industry 4.0. for instance, the aerospace sector has sometimes been characterised as "too low volume for extensive automation" however Industry 4.0 principles have been investigated by several aerospace companies, technologies have been developed to improve productivity where the upfront cost of automation cannot be justified, one example of this is the aerospace parts manufacturer Meggitt PLC's project, M4.

Here, the fourth industrial revolution (Industry 4.0) refers to the "confluence of technologies ranging from a variety of digital technologies (e.g. 3D printing, Internet of Things, advanced robotics) to new materials (e.g. bio or nano-based) to new processes (e.g. data driven production, Artificial Intelligence, synthetic biology)" (OECD, 2016). These technologies have the potential to revolutionise operations and supply chain management (Brennan et al., 2015; Holmström et al., 2016; Rüßmann et al., 2015; Fawcett and Waller, 2014; Waller and Fawcett, 2013). Industry 4.0 is not merely about integrating technologies, but it is about the whole concept of how future customer demands, resources and data are shared, owned, used, regenerated, exploited, organised and recycled to make a product or deliver a service, faster, cheaper, more efficiently and more sustainably (Spath, 2013). As such, Industry 4.0 requires a rethinking and shift in mindset of how products are manufactured and services are produced, distributed/supplied, sold and used in the supply chain; thus, it will drive significant structural theoretical evolution and revolution for operations and supply chain management. Whilst classical theories such as resource based view, institutional theory, chaos theory, systems theory, stakeholder theory, transaction economic cost theory, evolutionary theory to name a few may need reshaping, the issues of trust will become prominent in such a disruptive digital environment, driving major evolvement of technological singularity in the transformation process, where blockchain may play a central role with Internet of Things and Artificial Intelligence (Carter and Koh, 2018).

2. Introduction

So far, all the industrial revolutions that took place in the past two centuries is promoted by altering production mode enabled by a specific emerging technology at that time (Liao et al., 2017). The arrival of steam engine promoted the first industrial revolution; the application of electricity led to the second revolution, and the widespread use of information technology and electronics products support the third revolution (Liao et al., 2017). The recent popularisation of the internet of things (IoT) and cyber-physical system (CPS) (Khaitan & McCalley, 2014) has attracted the attention of both enterprise and academics. Leveraging those two emerging technologies is promising to enable the higher level of connection between information, products and people (Ibarra et al., 2018), thereby making contributions to the current production mode. This phenomenon is considered as the fourth industrial revolution, also known as industry 4.0, which is about to bring about an extensive range of innovation from a variety of digital technologies (Lu, 2017), advanced materials (Schumacher et al., 2016), innovative products (Pereira & Romero, 2017), to new manufacturing processes (Wagner et al., 2017).

Industry 4.0 is an emerging concept deriving from technological advancement and disruptive developments in the industrial sector worldwide in the past few years (Dallasega et al., 2017). It defines a methodology applying emerging technologies to revolutionize the current production that transits from machine dominant manufacturing to digital manufacturing (Ozteme & Gursev, 2018). Some consider it as the integration of technologies such as CPS, IoT, Big Dara and Cloud manufacturing (Pereira & Romero, 2017). However, there is a discourse arguing that industry 4.0 is not only regarding integrating technologies but concerning the whole concept of how to acquire, share, use, organise data and resource to make the product/service deliver faster, cheaper, more effective and more sustainable (Piccarozzi et al, 2018).

As the interest in the Industry 4.0 research is growing rapidly, these studies do not limit their focus on industry 4.0 itself, but seek to find the relationship between industry 4.0 and other topics. For instance, Piccarozzi et al. (2018) try to link industry 4.0 with management studies; Dallasega et al. (2018) investigate industry 4.0 in the context of the supply chain. Müller et al. (2018) and Kamble et al. (2018) explore the relationship between industry 4.0 and sustainable development.

This position paper intends to summarise the major topics in the current research regarding Industry 4.0 and charts key thematic future research directions and paradigms. In the following section, the paradigms and principles of industry 4.0 are concluded. Five technologies that are widely discussed in the current research are identified and the outcomes of industry 4.0 are discussed at the end of this position paper.

3. Paradigms in industry 4.0

According to Weyer et al. (2015), industry 4.0 can be subdivided into three paradigms: The Smart Product, the Smart Machine and the Augmented Operator. This conclusion of the major paradigm of industry 4.0 is also agreed by Longo et al. (2017) and Mrugalska and Wyrwicka, (2017). The first paradigm is the smart products, it refers to objects and machines that are equipped with sensors and microchips, controlled by software, and connected to the internet (Lu, 2017; Kamble et al., 2018). Smart products can store the operational data and requirements independently, and further, the product can inform the machine-related manufacturing information, for instance, when to produce, where to produce, or what parameter should be adopted to complete the product manufacturing. In this case, smart product shifts the role of the workpiece in a system from passive to an active part (Loskyll et al., 2012).

The second paradigm is the Smart Machine. It refers to a device equipped with machine-to-machine and/or cognitive computing technologies (i.e. artificial intelligence and machine learning). Through leveraging these technologies, machines can reason, problem-solve, make decision ad eventually take action. Smart machine brought decentralized self-organization, thus replacing the previous traditional production hierarchy (Mrugalska & Wyrwicka, 2017). In such innovative system, the use of open networks and semantic descriptions allow the communication among the autonomic components (Oztemel & Gursev, 2018), while the local control intelligence communicate with other devices, production modules and products, thereby, contributing to the improvement of flexibility and modularity of the production line (Pereira & Romero, 2017).

The third paradigm of industry 4.0 is the augmented operator. This concept emphasizes the technological support of the worker in the production system with higher flexibility and modularity (Weyer et al., 2015). Mrugalska and Wyrwicka (2017) state that augmented operator addresses the knowledge automation in the system, therefore making them the most flexible and adaptive part in the production system. Workers in such production system are likely to encounter with varieties of tasks including specification, monitoring and verification of production strategy. Meanwhile, they may have to annually intervene in the self-organized production system. Under the support of mobile, context-sensitive user interfaces and user-focused assistance system (Gorecky et al., 2014), such workers play the role of strategic decision-makers and flexible problem-solvers in the circumstance of increasing technical complexity (Mrugalska & Wyrwicka, 2017).

4. Design principles in industry 4.0

Based on the three paradigms mentioned above, some researchers further conclude six principles that should be considered when designing the implementation of industry 4.0 (Oztemel & Gursev, 2018). Those principles include interoperability, virtualization, decentralization, real-time capability, service orientation and modularity (Lu, 2017, Oztemel & Gursev, 2018). Kamblea et al. (2018) conduct a systematic literature review to develop a framework of sustainable industry 4.0 and further justify the role of these principles on industry 4.0 implementation.

First, interoperability is the first principle for industry 4.0. Interoperability refers to the ability of two systems to communicate with and understand each other and use the functions of one another (Hermann et al., 2016; Lu, 2017). It addresses the capability of data exchanging and information and knowledge sharing among systems (Lu, 2017). It is assumed that interoperability is the key advantages of industry 4.0 as it ensures the connection and communication among products, machines and humans (Mrugalska & Wyrwicka, 2017) throughout the diversified autonomous procedure (Lu, 2017).

Further, Lu (2017) proposes a framework of interoperability of industry 4.0 and concludes four levels of interoperability in industry 4.0, including operational, systematic, technical and semantic interoperability. The author gives specific explanations for each level of interoperability. Operational interoperability indicates the concepts, standards, languages and relationships within the system. Systematic interoperability describes the methodologies, standards and models.; technical interoperability illustrates tools and platforms for technical development, and the semantic interoperability ensures the exchanged information is well understood among different groups.

Qin et al. (2016) confirmed that interoperability constructs a trusted environment in a manufacturing system, in which information is accurately and swiftly shared among partners (Kamble et al., 2018), therefore resulting in a cost-saving operation with higher productivity (Lu, 2017).

Virtualization is used for process monitoring and machine-to-machine communication. It indicates that devices have the capability of monitoring the physical process. The sensor data is linked to virtual plant models and simulation models, thus constructing the virtual copy of physical objects (Mrugalska & Wyrwicka, 2017). Meanwhile, each device can be virtualized and become a part of the plant model. The virtual model can simulate various scenarios based on the monitored data. Once the potential risks or failures are detected in the virtual models, operators are informed and they can take the pre-emptive action (Kamble et al., 2018), thus reducing the actual error rate and smoothing the inter-company operations (Brettel et al., 2014).

Third, decentralization denotes that companies, operation staff, and even devices are able to make independent decision rather than depending on the centralized decision-making, It can be achieved with the use of embedded computer, which provides the operation staff or devices the capability of individual control and independent decision-making (Marques et al., 2017). As the development of customization and product variety, the flexible production line is expected to be extensively adopted. Overall control of the production line is less advisable. However, the embedded control system can empower each device or the unit of the device to make independent decisions, thus making the decision-making efficient and offering more flexibility (Kamble et al., 2018).

Fourth, real-time capability refers to the immediacy of data collection and analysis, and the real-time of data transmission. Smart factory requires continuous real-time data monitoring and analyzing, to detect the errors timely and satisfy the new demand. The collection of real-time data relies on big data technology (Kamble et al., 2018). The huge amount of data regarding machines, equipment, and products are collected from factories, and data regarding customers are collected from multiple sources such as social media or outlets. The analysis of those real-time data may alter the ways of decision-making and pose an impact on the profitability of the companies implementing industry 4.0.

Fifth, service orientation required that devices are capable of satisfying the needs of users through the Internet of Service (IoS). As all the entities in the production system are interconnected, and therefore, the concept of the product will extend from the product itself to product-service (Lasi et al., 2014). Service orientation indicates that product should be considering the users' practical needs, such as user-friendly or convenience for maintenance, at the very beginning of product design. Moreover, through service orientation, corporate can achieve flexibility and agility and thus to have a quick response to the market change (Kamble et al., 2018).

Sixth, modularity refers to the device or the components of a device is produced following standards. Therefore, they can be assembled, replaced and expanded as needed in the modular production system (Qin et al., 2016). In this case, modularity provides smart factories with the capability of adapting capacity at a lower cost to cope with seasonal fluctuation and changes in production needs (Mrugalska & Wyrwicka, 2017).

5. Technologies in industry 4.0

Lu (2017) defines industry 4.0 as an integrated, adapted, optimized, service-oriented and interoperable manufacturing process in which algorithms, big data, and high technologies are included. Technologies are considered as the very heart of industry 4.0 as the interconnection in the industry 4.0 is supported by the adoption of software, sensor, processor and communication technologies (Bahrin et al., 2016).

Five technologies are frequently discussed in the literature: Internet of Things (IoT), big data analytics, cloud, 3D printing, and robotic systems (Piccarozzi et al., 2018; Kamble et al. 2018), where technologies such as Artificial Intelligence (AI), Machine Learning (ML), digital twin and 5G are emerging.

Internet of Things (IoT)

The IoT is an emerging industrial ecosystem. It facilitates the combination of intelligent machines, advanced predictive analytics and machine-human collaboration, aiming at promoting productivity, efficiency and reliability (Kamble et al., 2018). In industry 4.0, IoT can support the smart factory. It can lead to the creation of virtual networks to support the smart factory (Xu et al., 2018); meanwhile, it provides the factory with the ability to collect real-time data and transmit the data swiftly (Yang et al., 2017). Therefore, it enables the remote operation of manufacturing activities and affects collaboration among stakeholders (Yang et al., 2017). IoT can benefit the integration and coordination of product and information flow (Tao et al., 2014), and enable the decentralization of decision-making, interconnected devised can perform automatic analytics and decision-making, thus improving the responsiveness to the environment change (Wang et al., 2014).

Big data analytics

Manufacturing companies have realized that data analytics capabilities are imperative for their competitive advantage in the era of digitization. Therefore, they devote themselves to improving skills for algorithms development and data interpretation (Lee et al, 2017). Big data analytics and technologies can promote data collection from multiple sources, and the ability of comprehensive data analysis and real-time decision making based on the data analysis results (Bahrin et al., 2016). It has been widely adopted in manufacturing to monitor the process. Also, big data is used for failure detection, thus supporting new capabilities such as predictive analytics (Lee et al, 2017). Data quality and qualified data analysis capabilities are key to achieve the desired outcomes of big data analytics (Kamble et al., 2018). Therefore, leveraging the intelligence in big data to improve agility will require new challenges, for example how to ensure the data consistency and confidentiality in a long and complex supply chain (Kamble et al., 2018).

Cloud

Cloud computing is a computing technology. Cloud computing centers can store and compute a huge amount of data, therefore promoting the manufacturing and production and further bringing organizations higher performance and lower cost (Mitra et al., 2017). Cloud computing is supported by virtualization technology, as it provides cloud computing with resource pooling, resource sharing, dynamic allocation, flexible extension, and other capabilities (Xu et al., 2018). Xu et al. (2018)

also address the usefulness of cloud computing in facilitating efficient data exchange and sharing. Through cloud computing, data can be stored in either private cloud or public cloud servers, and thus cloud computing can promote complex decision-making (Xu et al., 2018).

Cloud-based manufacturing is key to the success Industry 4.0 implementation. It enables the modularization and service-orientation in the field of manufacturing (Xu et al., 2018), where system orchestration and sharing of service and components are essential considerations and are affected by modularization and service-orientation (Xu et al., 2018). Branger and Pang (2015) assumed that cloud manufacturing is expected to be the next paradigm in manufacturing in Industry 4.0.

3D printing

3D printing relies on additive manufacturing (as opposed to subtractive manufacturing). Final products in 3D printing are built up with successive layers of materials (Oztemel & Gursev, 2018), thus avoiding the component assembly in the production process. Additive manufacturing techniques can make contributions to industry 4.0 in terms of offering organizations construction advantages, as it allows to produce small batches of customized products with complex and lightweight design (Kamble et al., 2018). Chen and Lin (2017) state that the exploitation of 3D technology can optimize smart manufacturing and lean manufacturing. However, there are technical challenges in the use of 3D printing, namely, limited accuracy and productivity, and limited available material (Chen & Lin, 2017). Because of the technical challenges, additive manufacturing (3D printing) is still in the initial stage. However, once the challenges have been solved, it is expected to see wider adoption of this technology in Industry 4.0 (Kamble et al., 2018).

Robotic systems

However, robotics has been used for production in many manufacturing industries, the modern robotics systems are more flexible, autonomous and smart and are able to communicate and cooperate with one another and even have learning ability (Kamble et al., 2018), leading to the next generation of robotic systems namely cobot (collaborative robots). Pei et al. (2017) state that the modern robotics can perform well in most of the processes in the smart factory, for instance, Mueller et al. (2017) proposed that it is feasible to use programmable dual-arm robots to efficiently distribute and allocate materials in the assembly line. Therefore, the application of modern robots can provide the factory with cost advantages and a wide range of capabilities (Pei et al., 2017). To ensure the safe operation of the robotics system, a device named safety eye is equipped. Once the device has detected any disturbance in the operation, it will stop the robot and will not reactivate the robot before the operators remove the objects that disturb the operation (Kamble et al., 2018).

6. Outcomes of industry 4.0

Considering industry 4.0 can revolutionize the products and manufacturing system in terms of operation, product, design, production processes and services across the supply chain, it is expected that implementing industry 4.0 can positively impact the industry, markets, and multiple participants (Dallasega et al., 2017). Pereira and Romero (2017) conclude six areas on which industry 4.0 may exert influence. Those areas include: industry, products and service, business model and market, economy, work environment and skills development. Kamble et al. (2018) further link industry 4.0 with sustainable development and argued that industry 4.0 can generate sustainable outcomes in terms of environmental, social and economic.

Industry 4.0 has brought manufacturing industry new decentralized and digitalized production patterns, in which the production elements are highly autonomous, and therefore they can trigger actions and respond to the environment change independently (Pereira & Romero, 2017). Industry 4.0 also promote the integration of products and processes, thus transforming the production pattern from mass production to mass customization (Lu, 2017). Additionally, production processes and operations are significantly affected by the emergence of smart factories and emerging technologies, such as IoT, 3D printing and robotic systems. in this case, Industry 4.0 can improve the flexibility in operations and efficiency in resource allocation (Pereira & Romero, 2017). Dallasega et al. (2018) state that Industry 4.0 will not only affect the productivity in the manufacturing industry but also influence the entire supply chain from product development and manufacturing process to the product distribution. Products and services are also affected by industry 4.0. The principle of modularisation makes the products modular and configurable, and as a result, products and services are more customised to satisfy specific customer needs (Jazdi, 2014).

Industry 4.0 has brought a number of new disruptive technologies that have altered the approaches of delivering products or services, hence affecting the traditional business models and encouraging the new business models (Pereira & Romero, 2017). For instance, system integration and complexity in industry 4.0 will result in the emergence of more complex and digital market models, in which the barriers between information and physical structure are reduced (Ibarra et al., 2018).

Industry 4.0 is transforming jobs and required skills, which have impacts on the working environment and skills development. With more robots and smart machines is involved in the daily operation, the physical and virtual world are fusing together, thus launching transformation in the working environment. For example, as human-machine interfere requires the communication among smart machines, smart products and employees, ergonomic issues should be considered in the future system should stress the workers and their importance in the system (Pereira & Romero, 2017). For skills development, as in the context of industry 4.0, interdisciplinary thinking and qualified skills in the social and technical field are required. These new competencies should be included in the employee training and education (Pereira & Romero, 2017), to make workers and managers well prepared for this new industrial paradigm.

Moreover, Kamble et al. (2018) state that Industry 4.0 can lead to sustainable development. With the support of cloud computing and big data analytics, organizations can achieve cost reduction and lean production, thus realising the economic sustainability; Employing technologies such as sensing, detection and tracing analysis can help to mitigate the problem of industrial waste disposal, which facilitates the environmental sustainability; technologies (risk maps or wearable technologies) for improving the safety of employees in hazardous work areas helps to ensure the process safety and promote the social sustainability.

7. Methodological approaches adopted by Industry 4.0 research

Industry 4.0 literature is characterized by a prevalence of conceptual papers. Piccarozzi et al. (2018) found for instance in their systematic review on Industry 4.0 in management studies 54% of conceptual papers, mainly literature reviews and developments of models/frameworks. As far as empirical papers are concerned, qualitative methods (mainly case studies) and quantitative methods (surveys) are almost equally adopted (25% vs. 21%, respectively).

An agreed definition and operationalization of the Industry 4.0 construct is missing (Culot et al., 2018). While some authors have indeed sought to develop maturity models and readiness indexes, which identify incremental levels of Industry 4.0 implementation (for a review see Mittal et al., 2018), Industry 4.0 literature still relies on different operationalizations of the concept. As an example, the bunch of technologies considered as Industry 4.0 varies significantly from one paper to the other. This poses serious limitations to theory building and research comparability.

Finally, Industry 4.0 papers belong to a wide set of disciplinary domains. Muhuri et al. (2019) identified in their bibliometric analysis of Industry 4.0 the top 10 subject areas in the Scopus database. At the first place there is Engineering (65%[1]), followed by Computer Science (45%), Business, Management and Accounting (16%), and Decision Sciences (14%). While these disciplines were the most important ones also in the previous investigation conducted by Liao and colleagues (2017), their relative importance has significantly changed (Engineering was at the second place after

[1] The sum of percentages exceeds 100% since some papers are categorized by Scopus in more than one category.

Computer Science; Business, Management and Accounting and Decision Sciences were significantly less frequent). Besides this wide set of disciplines involved, there is however a limited number of interdisciplinary papers.

8. Suggestions for future Industry 4.0 research – methodological approach

As we pointed out in this position paper, Industry 4.0 research so far is still characterized by a prevalence of conceptual papers in the operations and production field. However paradigms, design principles and technologies prevalent to industry 4.0 have been examined. Whilst this might be partially justified by the novelty of the topic and the consequent limited adoption by companies (the Industry 4.0 concept was indeed introduced at the Hannover Fair in 2011), the scientific research cannot overlook the contact with the industrial world. One of the main challenges for future Industry 4.0 research is therefore to ***carry out more empirical investigations as well as large-scale data analysis***. For this reason, we decided not to accept any conceptual contribution in our special issue (even though we received some high-quality conceptual papers). Alongside the traditional empirical methods (i.e., case study and survey), other exploratory methodologies – such as Delphi studies or focus groups – could bring significant insights given the interdisciplinary and "futuristic" nature of the topic.

A further potential methodological limitation of current Industry 4.0 research is the absence of agreed definitions and operationalizations of the main constructs. Without these operationalizations, there is a risk that the significant relationships observed are just due to the specific definitions considered and are not reproducible in other studies. A second significant challenge for future Industry 4.0 research is therefore to ***define the main Industry 4.0 constructs (e.g. Industry 4.0 adoption, Industry 4.0 maturity, Industry 4.0 readiness) and empirically validate them.*** This challenge will not be easy since both the technological landscape and the application fields of Industry 4.0 are rapidly evolving. Researchers should however find a way to define a common set of constructs to support further theory building and theory testing efforts.

The issue pointed out above is particularly significant in quantitative research, which is usually based on closed-ended questions or secondary data (requiring a precise operationalization of the measured constructs). The almost equal representation of qualitative and quantitative research might in this sense signal a potential issue. We therefore think that ***qualitative theory building papers should be particularly welcome in this stage***, to develop a set of constructs and relationships to be tested on larger samples in a later stage.

Finally, Industry 4.0 is a highly interdisciplinary topic, involving a wide set of knowledge domains (e.g., automatic controls, robotics, sensors, computer science, and management) and actors (e.g., researchers, companies, technology providers, policy makers, schools). The successful transition towards Industry 4.0 requires indeed a joint effort of the above-mentioned actors to create a successful ecosystem (Xu et al., 2018). ***Interdisciplinary research should therefore be significantly encouraged at all levels.*** *First*, Industry 4.0 researchers should for instance try to aim in their paper more at the policy makers and the managers. Research should indeed support the different authorities to take better decision to support the digital transformation. Second, authors from different disciplines or affiliations (universities, applied research centers, companies, technology providers, governments and regulatory bodies) should try to systematically integrate the different perspectives and point of views. Finally, the reviewing and editorial board of journals might also be broadened/hybridized by involving experts from the industrial and the policy making worlds.

9. Conclusion

The purpose of this position paper is to summarize the major topics of recent research on industry 4.0. First, three paradigms and six principles of industry 4.0 are identified, and five technologies that are frequently discussed in industry 4.0 are concluded. The outcomes and impacts of industry 4.0 are discussed at the end. In addition, the methodological approaches in industry 4.0 research has been discussed, and future research directions and paradigms of industry 4.0 methodological approach have been proposed.

Although industry 4.0 has been widely discussed from multiple perspectives, as technology advancement still takes place constantly, thus continuously shaping the industry and organizations, there are abundant research opportunities in this topic. Meanwhile, with the increasingly in-depth understanding of industry 4.0, there are more research potentials to combine industry 4.0 with other research fields, to further investigate the industry 4.0 with a wider scope.

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