

Industry 4.0 supporting Sustainable Development

Neaga Irina, Wales Institute of Science and Art, University of Wales Trinity St David, Swansea, United Kingdom,
e-mail: Irina.Neaga@uwtsd.ac.uk

Definitions

Industry 4.0 (I4.0) encompasses the developments, applications and implementation of several new technologies, and platforms that support extensive automation, data collection, exchange and processing within a Cyber-Physical Systems. The main technologies are as follows: Internet-of-Things (IoT), big data, augmented and virtual reality, additive manufacturing (3D printing), simulation systems, autonomous robots and cloud computing. I4.0 is strongly supporting sustainable development through an efficient application or adoption of all the new technologies and social media creating powerful industrial socio technical systems. Therefore, the vision of I4.0 is directed to enhance the sustainability and performances from the industrial processes—including engineering, material usage / consumption, manufacturing, supply chains, and product lifecycle management—to the horizontal business value chains defined as Business 4.0 and Supply Chain Management 4.0. Generally sustainable development is conceptually defined and supported by governments, foundations and world organizations including the United Nations which have defined the 17 Sustainable Development Goals (SDGs) detailed in 169 targets that are interconnected linking separate goals of sustainable development across different areas, into a unitary vision and holistic approach (United Nations 2015a, 2015b). The main aim of this contribution is to provide a holistic approach of the impacts of I4.0 to sustainable development goals as defined by United Nations.

Background

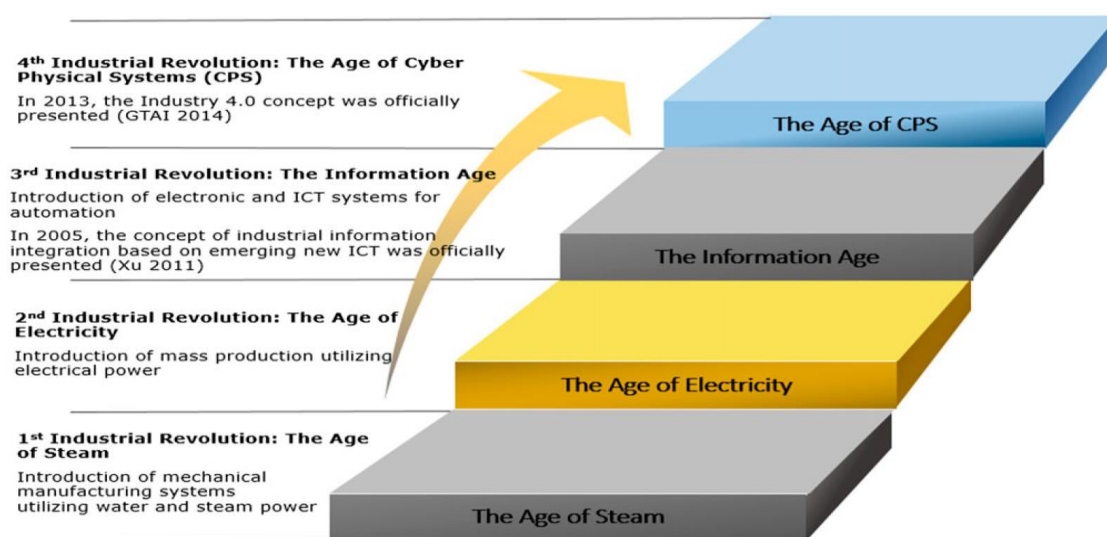


Figure 1. From Industry 1.0 to Industry 4.0 (Xu, Xu and Li, 2018)

The new United Nation's vision of sustainable development leads to move the focus beyond dedicated sustainability issues of environmental impacts of human and industrial activities, economic inequalities, equal access to quality education and jobs opportunities to the integration in a more coherent "system of systems" (United Nations 2015a, 2015b). Information and Communication Technologies (ICT) are an integral and essential part to support the achievement of the sustainable development goals (SDGs). On the other hand I4.0 represents the evolution of the Industrial Revolutions upon which Information and Communication Technologies (ICT) contribute to a digital infrastructure for innovative and more sustainable developments through the extensive adoption of technology based systems (Alexopoulos et al., 2016; Qin, Liu, and Grosvenor, 2016; Li, 2017; Xu, Xu and Li, 2018). This evolution is presented in figure 1

I4.0 includes technologies and platforms which are shown in figure 2. (Mourtzis et al. 2018; PWC, 2016; Xu, Xu and Li, 2018). Figure 2 also presents that the development of I4.0 is driven by digitalisation and integration of vertical and horizontal value chains, digitalisation of product and service offerings and the new digital business models and customer access platforms.

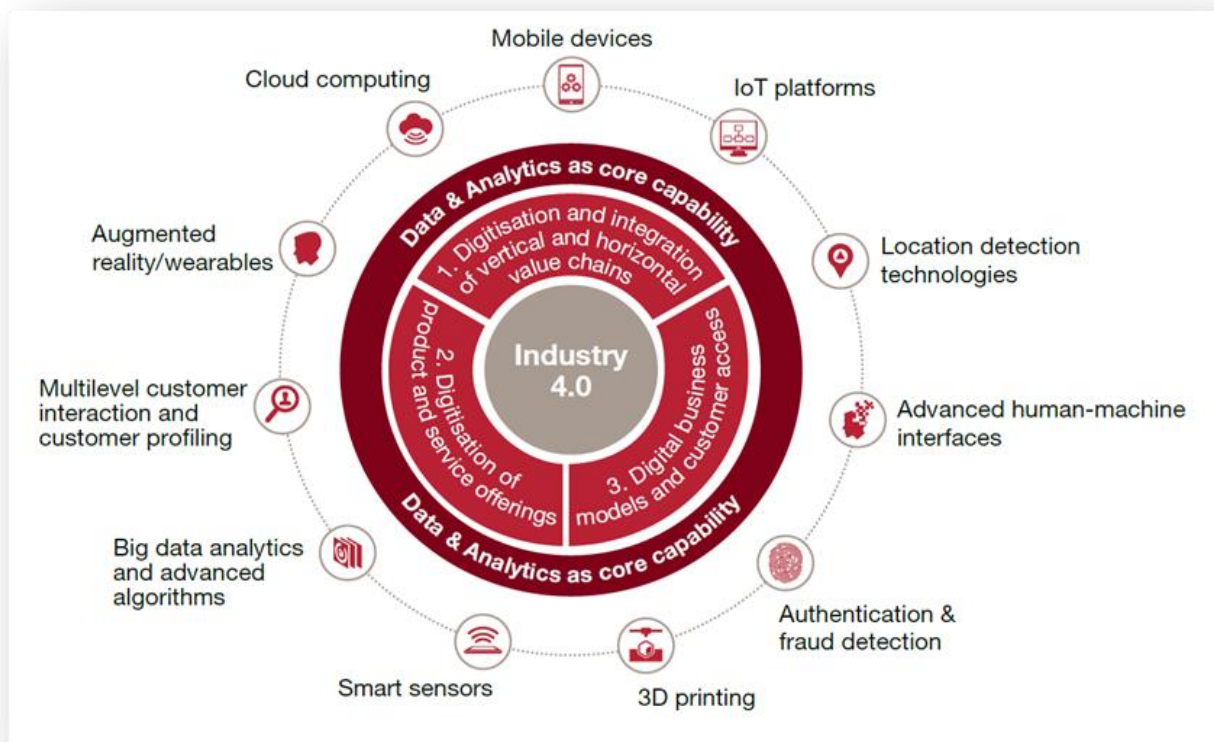


Figure 2. Industry 4.0 Framework (PWC, 2016)

I4.0 adoption leads to a new era for sustainable development that requires redesign of business processes and supply chains mainly as a major consequence of the digitalisation (Marr, 2016). Industry 4.0 has been applied by industrial companies, and governments in Germany, US, UK, China, India, and other European and Asian countries.

Industry 4.0 has influenced the supply chains planning, (re-)design and operations. The Supply Chain Management (SCM) in the era of I4.0 is defined as SCM 4.0 that represents a new stage of development in SCM, in which the coordination of materials, information and financial flows in corporate networks of circular economy is largely automated and permeated with digital technologies. Financial flows can be managed using blockchain that is based on a distributed ledger technology allowing information to be stored in shared databases and protecting the information from removal, corruption or unjustified modification (Beck et al. 2018; Lindman et al. 2017; Lage, 2019; Rossi et al. 2019)

Blockchain technologies are not explicitly included in I4.0 frameworks but the associated data technologies have a huge impact on the sustainable global and circular economy (CE) and hence this contribution will analysis the linkages between blockchain, I4.0 and sustainable development.

Introduction

- Industry 4.0 supporting Sustainable Development of Smart Factories

Nowadays, the industrial / production companies have a high level of automation, working more efficiently and are linked to computer networks (Givehchi et al., 2013). This means the machines can provide information to the company's databases. This development is based on one of the main ideas of Industry 4.0 supporting the development and deployment of a highly performing highly connected networks within the company and thus to develop and implement the smart/intelligent factory that could be flexible integrated in the

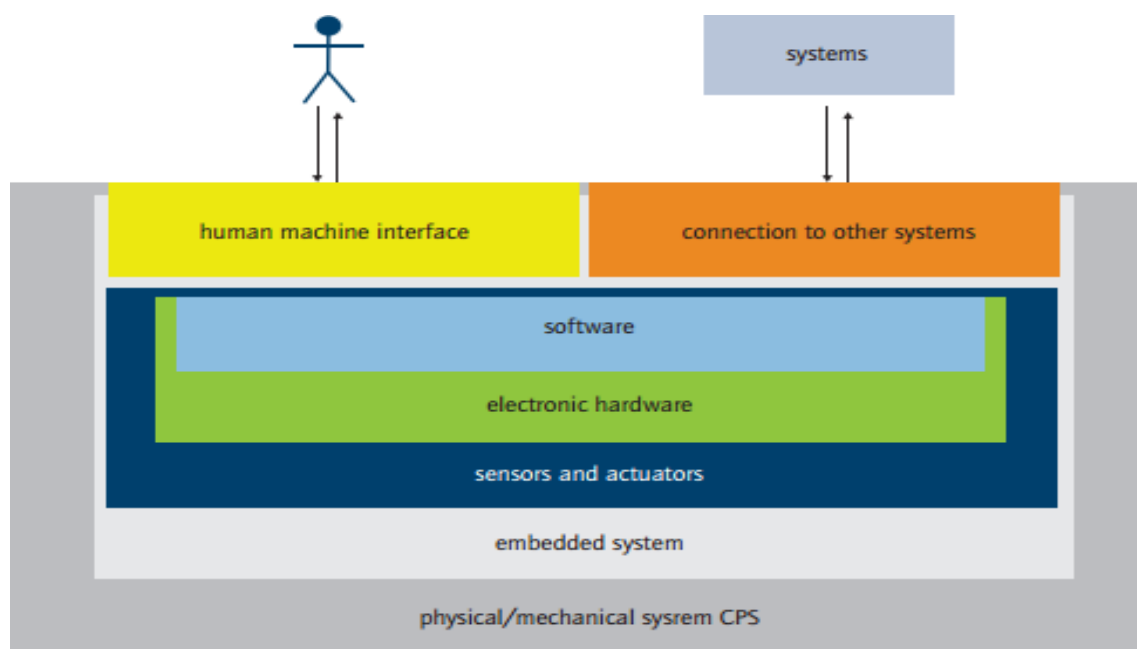


Figure 3. Cyber Physical System structure (Broy, 2015 p.24)

circular economy (CE). The development of an extremely flexible structure of production processes results in highly responsiveness of meeting customer requirements and the possibility of immediately realised amendments and innovation of products. This also includes the possibility of creating highly efficiency and competitive

advantages towards competitors (Zhou et al., 2015). Essentially, the smart factory is a strategic part of the innovation management and leads to rise the productivity in their industries (Zhou et al., 2015) without compromising the sustainability. In order to adopt Industry 4.0 into practice, an integration of an improved network structure is needed and this integration is defined as the Cyber Physical System (CPS) (Zhou et al., 2015)

According to Bondavalli et al. (2016:5) CPS represents “a system consisting of a computer system (the cyber system), the controlled object (a physical system) and potentially of interacting humans.”

The typology of the networking structure is the organisation behind Industry 4.0 (Maslarić et al., 2016) and manages the linkage between the network and the physical technologies (Lee et al., 2015). Figure 3 shows the view and the content of a CPS which demonstrates that CPS is “Systems of Systems” where different/dissimilar systems are closely linked to each other (Broy, 2010). The integration of both humans and robots is the focus of the Fifth Industrial Revolution (Industry 5.0) that will lead to effective synergic environments between humans and machines.

Big data and cloud computing are widely used in I4.0 environments being included and the related concepts, applications and systems are described in the next section.

- **Big Data, Cloud Computing, Internet-of-Things and Additive Manufacturing**

The development of Industry 4.0 embeds processing large amounts of data generated due to the increased automation and their evolution of becoming more and more intelligent (Bonci et al., 2016) as well as using social media. Big data is a concept that has being evolved since late 1990s, when Cox and Ellsworth (1997) defined it as large data sets that required additional storage and new computing processing software. Therefore initially big data was perceived as more problematic than bringing benefits to companies and organisations. Recently big data analytics have evolved into a value adding technique for organisations providing them with competitive advantages.

With the increased use of data transfer over the internet, organisations have accumulated large amount of data which provide insights into market trends, purchasing patterns, customer behaviour and maintenance cycles. In order to benefit of this opportunity, new disciplines such as big data business analytics (BDBA) and supply chain analytics (SCA) have emerged (Neaga et. al, 2015 Wang et al., 2016). Big data concept is characterised by the three Vs: volume, variety, and velocity (Shi et al., 2011, Lee et al., 2013). Further research and developments have added two further Vs: variability, value and/or veracity (Gandomi and Haider, 2015; Wei and Albert, 2013). The main big data characteristics are briefly described below:

Volume (amount of data) - by McKinsey Global Institute means that the concept of Big Data refers to datasets whose size exceeds the capacity of ordinary tools for collection, storage, management and analysis and as such it is connected with the technological capabilities to manage these large and dissimilar amounts of data.

Variety (variety of data) – Big Data is collected from a variety of sources, which are : transactional systems, social

networking sites or the internet. These data change dynamically and could be very unstructured, which means that they are not suited to traditional forms of analysis (they include, for example, images, video and content from social networking sites)

Velocity (the speed of generation of new data and analysis) – data analysis is carried out on Big Data in near real time, as the correct conclusions from the constantly flowing and changing data need to be implemented on an ongoing basis

Value (value data) – the general aim is to isolate the whole amounts of information to what is most important for us – this is why it is so important that the results reflect the actual conditions and led to the most favorable business activities. Big Data makes it possible to analyze the data at a more advanced level than traditional tools allowed. With this technology, even data which has been collected in various mutually incompatible systems, databases and websites is processed and combined to give a clear picture of the situation in which there is a specific company or human.

Big data analytics are the technics to generate a measurable value from data (Chen et al., 2012) and enhanced new methods of analysis (Braganza et al., 2017) having the foundation in data mining and knowledge discovery. Big data driven strategies support analysis of the high volume and variety of data collected from the application of the Internet-of-Things (IoT) (Aker and Wamba, 2017).

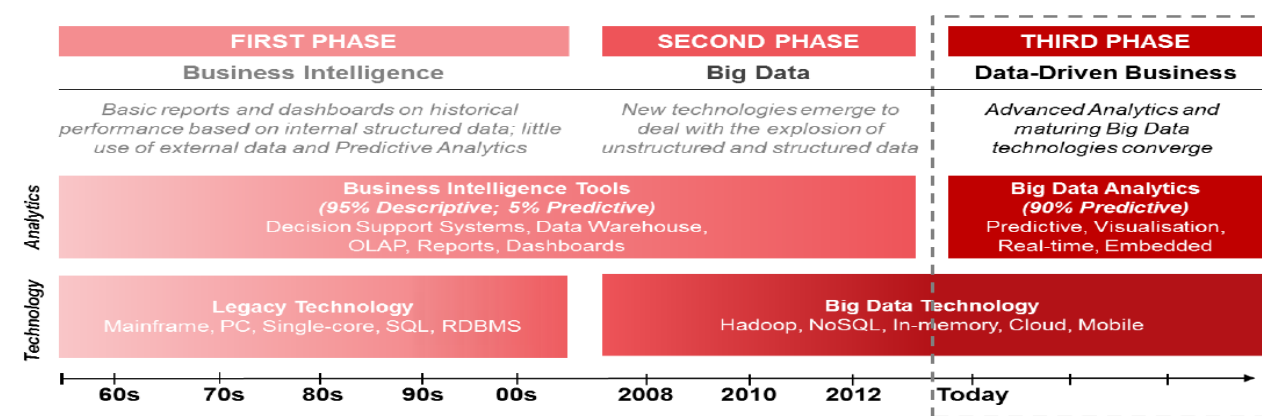


Figure 4. From business intelligence to big data analytics (GP_Bullhound LLP, 2013)

Furthermore, the analytics indicate the opportunity to deal positively with daily business challenges (Marín-Ortega et al., 2014) their traces and patterns leading at forecasting. Therefore big data should provide insights that support decision making (Gandomi and Haider, 2015). Big data could also be applied to improve product development (Zhan et al., 2016), demand forecasting in supply chains (Li et al. 2016) as well as green sustainable production (Du et al., 2016). Big data also supports the management of supply chain risk, enhanced sustainability, and the improvement of customer satisfaction (Davenport, 2014, Erevelles et al., 2016, Wang and Alexander, 2015). According to Manyika et. al. (2011) big data is critical for sustainable business success mainly as the amount of data increases continuously and it requires to be intelligently collected and processed in order to reveal trends, patterns that will support competitive advantages (Manyika et al., 2011). Big data analytics and related technologies support the solutions for effectiveness and efficiency in critical i applications such as energy savings,

sustainability, security and resilience (Sanders, 2014; McAfee and Brynjolfsson, 2012, Mayer-Schönberger and Cukier, 2013). The historic evolution of big data analytics systems is shown in figure 4 (GP_Bullhound LLP, 2013).

Cloud computing provides an environmentally friendly storage for integrated structured and unstructured data in an organised system via the Internet (Armbrust et al., 2009). Armbrust et al. (2010, p. 50) have defined cloud computing as an environment that “refers to both the applications delivered as services over the Internet and the hardware and systems software for data centers that provide those services.” This kind of services support handling of the huge amount of data. Both terms, big data and cloud computing, are “highly interdependent” (Yue et al., 2015, p. 1265). The growth of data collection and the possibility to transfer them in a cloud environment have an impact on the development to the Industry 4.0. Due to this, the possibility to develop more intelligent/smart factories becomes sustainable (Yue et al., 2015).

Lopes de Sousa Jabbour et. al, (2018a, b) have described the available technologies included in I4.0 that are contributed to sustainability providing a research agenda and a roadmap to support the implementation of Circular Economy (CE) principles in industrial companies and organisations using I4.0 technologies that are summarised below.

The concept of the Internet-of-Things (IoT) was firstly proposed by a British entrepreneur and founder of start-ups named Kevin Ashton who has formulated in 1999 a representation of a system in which the physical world communicates with computers (exchanges data) with ubiquitous sensors. About a decade later, at the turn of 2008 and 2009, the number of devices connected to the network exceeded the number of inhabitants of our globe. This moment, according to Cisco, is the initial step towards the Internet-of-Things, referred recently and to more often as the Internet -of -Everything”. In this approach, a system is created not only of objects but also the processes, data, people, and even animals or atmospheric phenomena – everything that can be treated as an object or variable. Three distinguishing features of the Internet of things are context, omnipresence and optimization. The first refers to the possibility of an advanced object interaction with an existing environment and the immediate response by it to change. The characteristic of context allows objects to provide information such as location, physical condition or atmospheric conditions. Omnipresence illustrates the fact that objects today are much more than just connections to a user network of human-operators. In the near future, they will communicate with each other on a large scale.

Therefore Internet-of-Things (IoT) refers to the interconnectivity between so called “things” that could be electronic devices, smartphones, machines, transportation means connected by internet, through unique identification codes which allow these things to communicate (Atzori et al., 2010; Gandomi et al., 2009). Using IoT cyber physical systems can be connected to companies/organisations and individuals, enabling interoperability with them. As a consequence, real-time data collection and sharing are able to occur among all parties (Zhong et al. 2013, 2017). The exchange of information between the things will generate a large quantity of data which can be subsequently analysed to improve added value for organisations (Roblek et al. 2016). Radio-frequency

identification (RFID) technology tags, sensors, barcodes, and smartphones are the most common resources used in implementing the internet of things (Atzori et al. 2010).

Radio frequency identification technology (RFID) is a development used to identify, collect and track goods materials that has replaced barcodes. If barcodes are used, the code must be in “a line of sight”. As RFID uses waves, a line of sight is not required to gather the information, saved on a RFID tag. RFID information associates tag-identifying data with arbitrary records. These records may contain product information, tracking logs, sales data, or expiration dates of products. Based on this, it is possible to build web-based applications to share information collected via RFID.

Additive manufacturing is based on the prototyping and visualisation of parts/sub-assemblies of products without the need to have and use specialised tools. Additionally, production occurs through digital design, which enables both a shortened leadtime on production and connectivity between designers, engineers, and users (Holmström et al. 2016). 3D printers are the main resources associated with additive manufacturing and generally the related concepts are overlapping and these are shortly described below (Ngo et al., 2018).

3-D printing is an additive manufacturing (AM) technique for fabricating a wide range of structures and complex geometries from three dimensional (3D) model data. The process consists of printing successive layers of materials that are formed on top of each other. 3D printing, which involves various methods, materials and equipment, has evolved over the years and has the ability to transform manufacturing and logistics processes. Additive manufacturing has been widely applied in different industries, including construction, prototyping and biomechanical. The uptake of 3D printing in the construction industry, in particular, was slower and limited despite the advantages e.g. less waste, freedom of design and automation. New applications are emerging as novel materials and additive manufacturing methods are continuously being developed. One of the main drivers for this technology to become more accessible is attributed to the expiry of earlier patents, which has given manufacturers the ability to develop new 3D printing devices. Recent developments have reduced the cost of 3D printers, thereby expanding its applications in schools, home, libraries and laboratories. Initially, 3D printing has been extensively used by architects and designers to produce aesthetic and functional prototypes due to its rapid and cost-effective prototyping capability. The use of 3D printing has minimised the additional expenses that are incurred in the process of developing a product. However, it is only in the past few years that 3D printing has been fully utilised in various industries from prototypes to products. Product customisation has been a challenge for manufacturers due to the high costs of producing custom-tailored products for end-users. On the other hand, applying additive manufacturing is possible to 3D print small quantities of customised products with relatively low costs. This is specifically useful in the biomedical field, whereby unique patient-customised products are typically required. Customised functional products are currently becoming the trend in 3D printing as predicted by Wohlers Associates, who envisioned that about 50% of 3D printing revolves around the manufacturing of commercial products from 2020 onwards. This technology has gained the attention of those in the medical field, due to its ability to produce a wide variety of medical implants. More recently, 3D printing is effectively being used in the

construction industry. Cheap / affordable houses in China (\$4800 USD per unit) were successfully mass printed by WinSun in less than a day. The growing consensus of adapting the 3D manufacturing system over traditional techniques is attributed to several advantages (Ngo et al., 2018) including achieving sustainability. The advantages of 3D printing technology continue to grow through research and development efforts, which must be undertaken to understand and eliminate constraints that inhibit the use of this technology. Design tools to assess life-cycle costs i.e., additive manufacturing-oriented computer-aided design (CAD) systems with more user-friendly and advanced simulation capabilities are some of the key aspects that need to be considered.

Sustainability, Circular Economy and Industry 4.0

Ellen MacArthur Foundation has presented the Circular Economy as “an industrial economy that is restorative or regenerative by intention and design” (2013: 14). Circular Economy (CE), and sustainable developments are gaining more attention in the academia, and industry and the definitions, similarities and differences between these concepts have been articulated. Sustainability and circular economy concepts initially was “blurring their conceptual contours and constrains the efficacy of using the approaches in research and practice” (Geissdoerfer et al., 2016:757).

Geissdoerfer et al. (2016) have discussed the relationship between the concepts and has been made it explicit based on systematic literature reviews, research and development. CE is an approach and strategy aiming at the sustainable use of resources and energy (McDowall et al., 2017). It is focused on maximizing the circularity or recycle of the resources and energy within industrial systems based on the reality that natural resources are scarce, and the waste at the end of products lives may retain some value (Ghisellini et al., 2016). Also the CE is a regenerative system in which input resources and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling. The sustainable development has been seen as the balanced integration of economic performance, social inclusiveness, and environmental resilience, to the benefit of current and future generations.

The principles, practices, and technologies of Industry 4.0 have enabled achieving the Circular Economy (CE) and sustainable developments especially of industrial/production systems.

Lopes Sousa Jabbour et al. (2018a, 2018b) have recently discussed that the Industry 4.0-associated technologies have the potential to support environmentally-sustainable development and the critical success factors (CSF) are identified through literature based research. The CSF are considered to pose challenges and opportunities to the process of simultaneously implementing Industry 4.0 and sustainable development especially in manufacturing industry. The approach adopted for sustainable manufacturing is related to environmental issues. This work makes the case for integrating two industrial waves that promise to re-shape current patterns of production and consumption: Industry 4.0 and environmentally-sustainable manufacturing. Lopes Sousa Jabbour et al. (2018b) have argued that Industry 4.0-associated technologies nevertheless have the unique potential to unlock

environmentally-sustainable manufacturing practices. Productive synergy between Industry 4.0 and environmentally-sustainable manufacturing relies on understanding the role played by eleven critical success factors, which organisations should consider carefully when simultaneously implementing Industry 4.0 and environmentally-sustainable manufacturing companies. As this is one of the first works to address whether or not Industry 4.0 can synergistically boost environmentally-sustainable manufacturing – with an emphasis on the critical success factors that can pose challenges and opportunities to this process leading to an integrative framework containing some research propositions and paradigms.

Also in the in the context of sustainable production company, Lopes de Sousa Jabbour et al. (2018b) proposed a roadmap to enhance the application of circular economy principles in organizations/companies within the Industry 4.0 environment aiming at the sustainable use of natural resources leading to CE that is presented in figure 5.

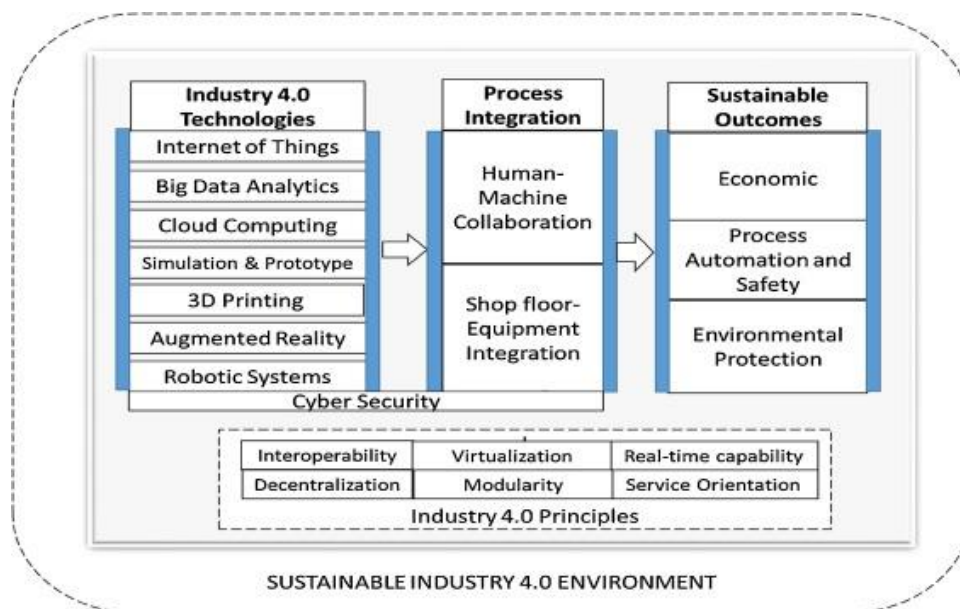


Figure 5. Developing Sustainable Industry 4.0 Environments

The Internet of Things (IoT) has the potential to extend the lifetimes of assets and products, reduce their in-use consumption, and support their effective recovery. Weetman (2017) has discussed the concerns about risks of privacy, security breaches and hacking in the systems. Despite these concerns companies are using IoT to connect their products leading at asset tracking and provide revenue-earning services for customers.

Big data collected from connected devices / things enables analysis of information on energy use, asset utilisation and materials flows providing insights that contribute to improve efficiency and reduce waste and consumption. Data centres in the cloud reduce energy costs for computer servers.

Autonomous technology machines act independently of humans and IoT supports autonomous vehicles such as drones and self-driving cars.

Knudsen and Kaivo-oja (2018) have provided details about the opportunities for increased sustainability and achieving the full benefits of CE by using novel technologies developments particularly within I4.0 in combination with new business models. Improved traceability of smart products through the entire supply chain and during the products' use phase allow manufacturers continuously to optimize the performance of both product and production, which will deliver a more efficient use of resources and energy. For industrial practitioners sustainability, circular economy, and social opportunities are also a driver for implementation of Industry 4.0 as presented in figure 6.

Figure 6. attempts to demonstrate that CE is supporting to develop and implement Industry 4.0 and also I4.0 is supporting circular economy. Therefore the challenges to simultaneously build a sustainable Industry 4.0 and to use Industry 4.0 for sustainable development are as follows (Knudsen and Kaivo-oja, 2018):

- 1. Ensure to the widest extent possible sustainability and circular economy as a feature in the Industry 4.0 framework;*
- 2. Explore and exploit the enabling potential of Industry 4.0 for building more sustainable business models and production systems.*

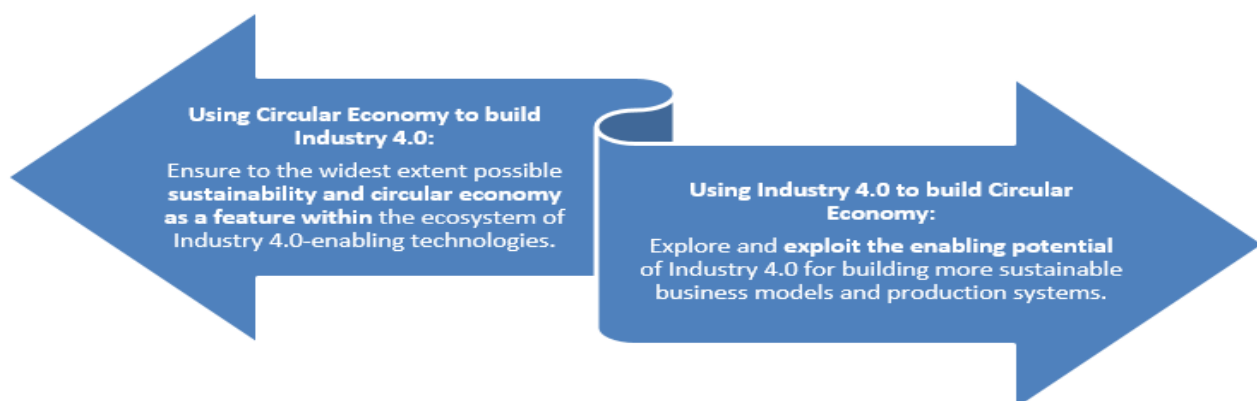


Figure 6. CE for I4.0 and I4.0 for CE (Knudsen and Kaivo-oja, 2018)

Blockchain and Industry 4.0 for Sustainable Development

Blockchain is defined as a decentralized, transactional database technology that facilitates validated and trusted transactions consistent across a large number of heterogeneous network participants or collaborators defined as nodes (Beck et al. 2018). Blockchain could be a solution to connect and manage IoT devices safely and reliably.

Conceptual approaches and frameworks of blockchain technology as well as empirical studies have recently moved beyond the original consideration of blockchain applications in the financial sector exclusively, and have envisioned the great potentials to a much wider application areas (Lindman et al. 2017; Lage, 2019; Rossi et al. 2019) leading at bridging the gaps between blockchain and Industry 4.0 particularly in the areas of sustainable developments.

However the main issue would remain to bridge the automation adopting I4.0 that provides the smart factories with the capabilities to produce much shorter and customized series of products at increasingly competitive prices, even tackling the manufacture of thousands of different configurations of a single base product. In order to achieve this, our production processes must have a flexibility in their configuration that have never been possible. This flexibility and ability to adapt automatically to demand at the core of the I4.0. Based on proofs of concept in the automotive, aeronautics, agri-food, or energy sectors Lage (2019) demonstrates that blockchain technology brings benefits to Industry 4.0 applications despite it is not explicitly included in the I4.0 Framework presented in figures 2 and 5. Therefore blockchain could enable sustainability regarding the following aspects:

- enhancing the transparency or visibility and synchronisation of sharing information between industrial systems and their supply chain networks;
- reducing information asymmetry especially in resource consumption management;
- incentivising circular economies thorough sustainable management of the financial flows.

Generally existing approaches and empirical research on blockchain have not focused on sustainable development. Lage (2019) in the context of blockchain research and applications addresses sustainability in relation to the ecological footprint of blockchain technology itself – i.e., the high energy consumption required by the computing-intensive processes, such as the blockchain proof-of-work consensus mechanism, that characterize blockchain. There are a few blockchain applications in the areas of Sustainable Development Goals (SDGs) such as humanitarian aid (Coppi and Fast 2019), gender equality (Kamath, 2018), or optimising energy usage and consumption. Moreover Medaglia and Damsgaard (2020) have proposed a detailed research agenda of blockchain technologies for sustainable development supporting all aspects of the SDGs, including poverty relief, equal quality education, institutional policies for sustainability, and responsible consumption.

The combined between IoT and blockchain have been applied by large companies. For example, Groupe Renault is prototyping a blockchain based system to store the digital twins of its vehicles to provide a single source of evidence for each vehicle's maintenance data. With this system, each vehicle's maintenance historical data remains connected to the vehicle even when there is a change of vehicle ownership. On the other hand, Bosch is also implementing digital twins of vehicles with a German certification authority to prevent illegal odometer manipulation. In the aviation and automotive industries, fake spare parts are a business problem and cause serious safety issues for several original equipment manufacturers (OEM). By using blockchain, all aspects related to the asset can be securely recorded. Fake used parts of a machine can be identified when being installed into a new configuration. When a combination of several components is determined, each component can cross-check the validity of the parts and the entity formed from the components.

However it is still a lack of elaborated studies demonstrating the potential of blockchain for sustainable development and as such an urgent need to encourage and channel research efforts towards blockchain applied for sustainable developments of industrial systems and their supply chains is required (Hughes et al. 2019).

Conclusions

This contribution presents a review of the I4.0 technologies and platforms supporting the sustainable developments and the integration of these technologies with blockchain to enhance environmentally sustainable industries and their supply chains leading at the implementation of circular economy.

. It also analyses the relationships between sustainability and the circular economy concepts and principles and how these concepts are connected. This approach demonstrates that Industry 4.0 technologies can unlock the full potential of environmentally sustainable development based on SDGs defined by UN. Industry 4.0 can boost the intelligent / smart factories by enabling producing green products, greening the production processes, and supply chain management. This approach also contributes to the existing literature by discussing a variety of Industry 4.0 technologies that can underpin CE strategies, and useful to the organisations by addressing those technologies on which they can base sustainable developments. However there are major challenges and particularities in various industries that should be supported by suitable regulations and policies that will be reinforced by further studies demonstrating the positive impacts of the CE and Industry 4.0. Therefore an elaborated strategic approach of these connected areas requires additional research work at both the conceptual/theoretical and practical levels but it is hoped that this contribution will stimulate the debate on the intersection of more sustainable developments, the integration of Industry 4.0 and environmentally- sustainable industrial developments.

Cross-References

[Development of New Skills: Innovation and Sustainability in Industry 4.0](#)

References

- Armbrust, M., Fox, A., Griffith, R., Joseph, A.D., Katz, R., Konwinski, A., Lee, G., Patterson, D., Rabkin, A. and Stoica, I. (2009, 2010). A view of cloud computing, Commun. ACM, 53 (4):50–58.
- Akter, S., and Wamba, S. F. (2017). Big data and disaster management: A systematic review and agenda for future research. Annals of Operations Research. <https://doi.org/10.1007/s10479-017-2584-2>.
- Atzori, L., Iera, A., & Morabito, G. (2010). The internet of things: A survey. *Computer Networks*, 54(15), 2787–2805.
- Babiceanu, R.F. and Seker, R. (2016). Big Data and virtualization for manufacturing cyber-physical systems: A survey of the current status and future outlook. Emerging ICT concepts for smart, safe and sustainable industrial systems, 81:128– 137.
- Beck, R., Muller-Bloch, C., and King, J. 2018. *Governance in the Blockchain Economy: A Framework and Research Agenda*, Journal of the Association for Information Systems (19:10), pp. 1020 – 1034.
- Bonci, A., Pirani, M. and Longhi, S. (2016). A database-centric approach for the modeling, simulation and control of cyber-physical systems in the factory of the future- 8th IFAC Conference on Manufacturing Modelling, Management and Control MIM 2016Troyes, France, 28—30 June 2016, Vol. 49 No. 12, pp. 249–254.

-
- Bondavalli, A., Bouchenak, S. and Kopetz, H. (2016). Cyber-Physical Systems of Systems, Vol. 10099, Springer International Publishing, Cham.
- Botta, A., Donato, W. de, Persico, V. and Pescapé, A. (2016). 'Integration of Cloud computing and Internet of Things: A survey'. *Future Generation Computer Systems*, 56:684–700.
- Braganza, A., Brooks, L., Nepelski, D., Ali, M. and Moro, R. (2017). Resource management in big data initiatives: Processes and dynamic capabilities, *Journal of Business Research*, Vol. 70, pp. 328–337.
- Broy, M. (2010). Cyber-physical Systems: Innovation durch softwareintensive eingebettete Systeme, Acatech DISKUTIERT, Springer, Berlin.
- Cox, M. and Ellsworth, D. (1997). Application-Controlled Demand Paging for Out-of-Core Visualisation. Proceedings of the 8th conference on Visualization '97, [online] 235-ff. Available at: <http://dl.acm.org/citation.cfm?id=266989.267068> [Accessed 03 June 2020].
- Chen, H., Chiang, R.H.L. and Storey, V.C. (2012). Business intelligence and analytics: From big data to big impact. *MIS quarterly*, 36(4): 1165–1188.
- Davenport, T. H. (2014). 'How strategists use "big data" to support internal business decisions, discovery and production'. *Strategy & Leadership*, 42 (4): 45– 50.
- Ellen MacArthur Foundation (EMF) (2013, 2014). Towards the Circular Economy, Isle of Wight.
- Erevelles, S., Fukawa, N. and Swayne, L. (2016). Big Data consumer analytics and the transformation of marketing, *Journal of Business Research*, 69 (2): 897– 904.
- Gandomi, A. and Haider, M. (2015). Beyond the hype: Big data concepts, methods, and analytics, *International Journal of Information Management*, 35 (2): 137– 144.
- Geissdoerfer, M., Savaget, P., Bocken, N. M.P and Hultink, E.J. (2016) The Circular Economy – A new sustainability paradigm?, *Journal of Cleaner Production*, 143: 757-768,
- Ghisellini, P., Cialani, C., and Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, 114:11–32.
- Givehchi, O., Trsek H. and Jasperneite J. (Eds.) (2013). Cloud computing for industrial automation systems — A comprehensive overview, IEEE 18th Conference on Emerging Technologies & Factory Automation (ETFA).
- GP_Bullhound LLP (2013) – Big Data Analytics – Extracting Insights from Exabytes, whitepaper
- Holmström, J., Holweg, M., Khajavi, S. H., and Partanen, J. (2016). The direct digital manufacturing (r) evolution: Definition of a research agenda. *Operations Management Research*, 9(1–2), 1–10.
- Kleindorfer, P. R., Singhal, K., & Wassenhove, L. N. (2005). Sustainable operation management. *Production and Operations Management*, 14(4): 482–492.

Knudsen, M.S. and Kaivo-oja, J. (2018) Bridging Industry 4.0 and Circular Economy: A New Research Agenda for Finland, online at <https://ffrc.wordpress.com/2018/09/12/bridging-industry-4-0-and-circular-economy/> accessed on 18.06.2020

Lage, O. (2019) Blockchain: From Industry 4.0 to the Machine Economy, IntechOpen, OA Books.

Laney, D. (2001), 3D data management: Controlling data volume, velocity and variety. *META Group Research Note*, Vol. 6: 70.

Lee, J., Ardakani, H.D., Yang, S. and Bagheri, B. (2015). Industrial Big Data Analytics and Cyber-physical Systems for Future Maintenance & Service Innovation, *Proceedings of the 4th International Conference on Through-life Engineering Services*, Vol. 38, pp. 3–7.

Lee, J., Bagheri, B. and Kao, H.-A. (2015), 'A cyber-physical systems architecture for industry 4.0-based manufacturing systems'. *Manufacturing Letters*, 3:18–23.

Lee, J., Kao, H.-A. and Yang, S. (2014). Service Innovation and Smart Analytics for Industry 4.0 and Big Data Environment, *Product Services Systems and Value Creation. Proceedings of the 6th CIRP Conference on Industrial Product-Service Systems*, 16:3–8.

Lopes de Sousa Jabbour, A.B., Jabbour, C.J.C., Godinho Filho, M. G. (2018a) Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations. *Ann Oper Res* 270, 273–286.

Lopes de Sousa Jabbour, A. B., Jabbour, C. J.C, Foropon, C., and Godinho Filho, M. (2018b). When titans meet - Can Industry 4.0 revolutionise the environmentally sustainable manufacturing wave? The role of critical success factors. *Technological Forecasting & Social Change*, 132: 18-25.

Manyika, J., Chui, M., Brown, B., Bughin, J., Dobbs, R., Roxburgh, C. and Byers, A.H. (2011). Big data: The next frontier for innovation, competition, and productivity, McKinsey Global Institute.

Marín-Ortega, P.M., Dmitriyev, V., Abilov, M. and Gómez, J.M. (2014). ELTA: New Approach in Designing Business Intelligence Solutions in Era of Big Data. *Procedia Technology*, 16: 667–674.

Marr, B. (2016) What Everyone Must Know About Industry 4.0. *Forbes Magazine*. Available at: <https://www.forbes.com/sites/bernardmarr/2016/06/20/what-everyone-must-know-about-industry-4-0/#4f4de065795f> (Accessed: 4 March 2017).

Maslarić, M., Nikoličić, S. and Mirčetić, D. (2016). Logistics Response to the Industry 4.0: the Physical Internet'. *Open Engineering*, 6:1.

Mayer-Schönberger, V. and Cukier, K. (2013). Big data. Boston: Houghton Mifflin Harcourt.

McAfee, A. and Brynjolfsson, E. (2012). Big Data: The Management Revolution. *Harvard Business Review*, 10:62-63.

McDowall, W., Geng, Y., Huang, B., Barteková, E., Bleischwitz, R., Türkeli, S., & Doménech, T. (2017). Circular economy policies in China and Europe. *Journal of Industrial Ecology*, 21(3), 651–661.

-
- Medaglia, R. and Damsgaard, J. (2020) Blockchain and the United Nations Sustainable Development Goals: Towards an Agenda for IS Research, *Proceedings of Twenty-Fourth Pacific Asia Conference on Information Systems, Dubai, UAE, 2020*, 1-11.
- Neaga, I., Liu, S., Xu, L., Chen, H. and Hao, Y. (2015). Cloud Enabled Big Data Business Platform for Logistics Services: A Research and Development Agenda. *Decision Support Systems V – Big Data Analytics for Decision Making*.
- Ngo, T. D., Kashani, A., Imbalzano, G. Nguyen, K. T.Q. and Hui, D. (2018), Additive manufacturing (3D printing): A review of materials, methods, applications and challenges, *Composites Part B: Engineering*, Vol. 143 pp 172-196
- Qin, J., Liu, Y. and Grosvenor, R. (2016). 'A Categorical Framework of Manufacturing for Industry 4.0 and Beyond', *Procedia CIRP*, 52:173–178.
- Roblek, V., Meško, M., & Krapež, A. (2016). A complex view of Industry 4.0. *SAGE Open*, 6(2), doi: [10.1177/2158244016653987](https://doi.org/10.1177/2158244016653987).
- Sanders, N.R. (2014) Big Data Driven Supply Chain Management – A Framework for Implementing Analytics and Turning Information to Intelligence. Person Education.
- Shi, J., Wan, J., Yan, H. and Suo, H. (2011). 'A survey of Cyber-Physical Systems'. *Wireless Communications and Signal Processing (WCSP)*, International Conference on 9 November 2011, Nanjing, China.
- Sipsas, K., Alexopoulos, K., Xanthakis, V. and Chryssolouris, G. (2016), 'Collaborative Maintenance in flow-line Manufacturing Environments: An Industry 4.0 Approach'. *Procedia CIRP*, 55: 236–241.
- Stock, T. and Seliger, G. (2016), Opportunities of sustainable manufacturing in Industry 4.0. *Procedia CIRP*, 40:536–541.
- Swaminathan, S. (2012) The effects of big data on the logistics industry', *Profit Oracle*. United Nations. 2015a. "Transforming Our World: The 2030 Agenda for Sustainable Development," United Nations. (<https://sustainabledevelopment.un.org/post2015/transformingourworld>).
- United Nations. (2015) About the Sustainable Development Goals, United Nations Sustainable Development. (<https://www.un.org/sustainabledevelopment/sustainable-development-goals/>, accessed 7 June 2020).
- Wang, G., Gunasekaran, A., Ngai, E. and Papadopoulos, T. (2016). Big data analytics in logistics and supply chain management: Certain investigations for research and applications. *International Journal of Production Economics*, 176: 98-110.
- Wang, L. and Alexander, C.A. (2015). Big Data Driven Supply Chain Management and Business Administration'. *American Journal of Economics and Business Administration*, 7(2): 60–67.
- Wei F. and Albert B. (2013). Mining big data: current status, and forecast to the future', *SIGKDD Explor. Newsl.*, 14(2): 1–5.
- Weetman, C. (2017) A Circular Economy Handbook for Business and Supply Chains, Repair, Remake, Redesign, Rethink, Kogan Publishing.

-
- Yue, X., Cai, H., Yan, H., Zou, C. and Zhou, K. (2015). Cloud-assisted industrial cyber- physical systems: an insight, *Microprocessors and Microsystems*, 39 (8): 1262–1270.
- Zhong, R.Y., Dai, Q.Y., Qu, T., Hu, G.J., Huang, G.Q. (2013) RFID-enabled real-time manufacturing execution system for mass-customization production. *Robot Com-Int Manuf*, 29(2):283–92.
- Zhong, R.Y., Xu, X., Klotz, E., Newman, S.T. (2017) Intelligent Manufacturing in the Context of Industry 4.0: A Review, *Engineering*, 3 (5): 616-630.
- Zhou, K., Liu, T., and Zhou, L. (2015). Industry 4.0: Towards future industrial opportunities and challenges. *In Fuzzy Systems and Knowledge Discovery (FSKD), August 2015 12th International Conference* (pp. 2147-2152).
- Xu, L. D., Xu, E.L., and Li, L. (2018) Industry 4.0: state of the art and future trends, *International Journal of Production Research*, 56:8, 2941-2962.