APPLYING INDUSTRY 4.0 TO SUPPORT SUSTAINABILITY AND CIRCULAR ECONOMY

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Abstract

The historical evolution of the 4th Industrial Revolution is broadly defined as Industry 4.0 (I4.0) and it is characterized by extensively adopting and applying Information and Communication Technologies (ICT) directed to build the an infrastructure that supports innovative, performant and sustainable industrial production and supply chains through the development, and implementation of technology and artificial intelligence systems. Industry 4.0 has been adopted by industrial companies, and governments, US, Europe, China, India leading to enable the sustainability and performances of the companies. The technologies, platforms and systems supporting the sustainable developments and the integration of these technologies enhance environmentally sustainable industries and their greener supply chains that are also directed to the circular economy. The research in progress reported in this paper demonstrates the increasing positive impacts of the application of I4.0 in industry supporting sustainability and circular economy. The research discusses solutions for the adoption of I4.0 technologies based on a systematic review of existing approaches that include application of Internet of Things (IoT), big data, additive manufacturing or 3D printing, digital twins, blockchain and cloud based computing. This project aims at developing a framework and methodology for an effective application or adoption of I4.0 technologies for sustainability and building the circular economy (CE).

Keywords*: Industry 4.0 (I4.0), Sustainability, Circular economy (CE), I4.0 Technologies, green supply chains*

1. INTRODUCTION

Industry 4.0 (I4.0) has emerged as part of the Fourth Industrial Revolution developing and implementing Information and Communication Technologies (ICT) systems directed at building an infrastructure for innovative, efficient and sustainable industrial and business developments through an efficient implementation and adoption of technologies based systems. I4.0 framework is presented in figure 1 (PWC, 2016); and it has been used by industrial companies, and governments in Germany, US, UK, China, India, and other European and Asian countries. I4.0 include the developments, applications, and implementation of new technologies, platforms and system that enable automation, data collection, exchange, and processing within a cyber-physical industrial system. The main technologies are as follows: Internet of things (IoT), big data, augmented and virtual reality, 3D printing (additive manufacturing), simulation systems, digital twins, autonomous systems, blockchain, and cloud computing. I4.0 is strongly supporting sustainable development through an efficient application or adoption of all the new technologies and powerful industrial socio-technical systems. Therefore I4.0 is directed to enhance the sustainability without compromising performances of the industrial processes including engineering, designing, material usage/consumption, manufacturing, supply chains, and product life cycle management. The application of I4.0 is leading to a more performant business value chains defined as Business 4.0 and Supply Chain Management 4.0 implemented within the smart factory (Factory 4.0).

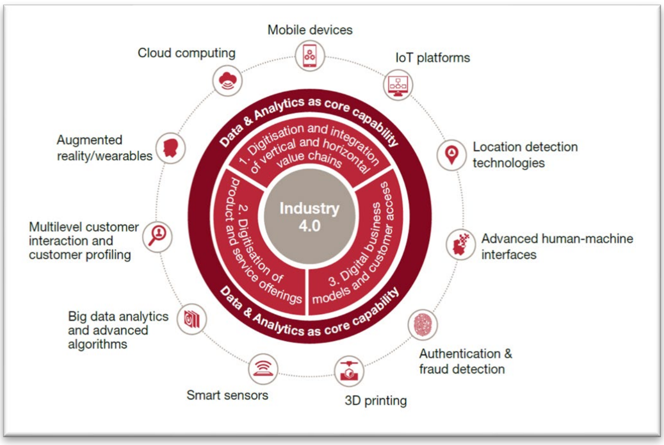

Figure 1. I4.0 Technologies, platforms and systems (PWC, 2016)

2. AIM AND OBJECTIVES

The main goal of this research is to develop a holistic analysis of the I4.0 technologies and their application in order to maximize the benefits and address the challenges for achieving sustainability and the circular greener economy as required by Net Zero strategies. This research in progress leads at developing a comprehensive multidisciplinary framework and methodology for a more effective application or adoption of I4.0 technologies for sustainability and building the circular economy (CE). The related objectives are as follows:

1. Providing an analysis of the current state-of-art of the application of I4.0 in industry using a systematic review of the literature and industrial reports.
2. Critically discussing the strategies of the application of I4.0 for sustainability of industrial automated production (i.e. smart manufacturing leading and smart factory) and digital supply systems.
3. Developing a holistic circular economy framework applicable in industries and to support greener supply chains.

3. SUSTAINABLE COMPETITIVE ADVANTAGES DRIVEN BY I4.0

Application of I4.0 has improved the following critical aspects based on digitalization (Santos et al., 2017):

1. Resource efficiency utilization leading at the sustainability of industrial systems and their green supply chains;
2. Development of more responsive and resilient industrial and supply chain systems;
3. Creating human-oriented systems that will improve work conditions, job satisfaction and employees well beings.

I4.0 aims to further develop and increase the benefits of digitalization of industrial companies and supply chains, facilitating the communications and synergies between people, machines and products and hence enabling greater real time access to production lines and supply chain information directed to the performant autonomous work processes and the economic value chains (Xu et.al.,2018). The industrial production sectors in Europe will achieve a growth from 15% to 20% by 2030 if it fully applies the digitization of their economic value chains (TSP Forum, 2015). Also according to Santos et al. (2017) the digitalization of supply chain applying I4.0 can bring positive benefits for sales and operations planning of manufacturers, such as reducing the time to respond to unforeseen or disruptive events affecting orders (around 300% improvement), to deliver orders (around 120% improvements) and time-to-market (approximately 70% improvement) as well as responsive inventory management systems. Some of the technologies associated with Industry 4.0 and their benefits are described as follows:

- Computer-Aided Design, Production Planning and Manufacturing (CAD/CAPP/CAM) systems that support the effective and efficient development, and running of projects and work planning for product manufacturing using advance computer based systems and applications;
- Integrated engineering management, business and supply chain systems that support information exchange and processing for product design, development and manufacturing;
- Digital Product Service Systems that are using computer based services and IoT platforms, embedded sensors, processors, and software systems for new capabilities. IoT based solutions embed electronics, software, sensors, and network connectivity into devices or entities (i.e."things") in order to allow the collection and exchange of data through the internet.
- Blockchain which is developed as a transactional distributed database that facilitates the validation and trusted transactions consistent across large number of heterogeneous networks and collaborators implemented as nodes (Beck et al. 2018). Cryptocurrency is also part of blockchain technology and it is increasing rapidly. This new economic trend called cryptoeconomics, can support sustainable developments and trusted financial systems. Therefore blockchain is an efficient solution to connect and manage IoT devices safely and reliably leading to support sustainability as follows:
  - Providing the transparency or visibility and synchronization of sharing information between industrial systems and their supply chain networks;
  - Reducing information overload and asymmetry for resource consumption management systems;
  - Developing the circularity of economies thorough sustainable management of the financial flows.
- Automation that is based on systems with embedded sensor technology for monitoring through data collection, integration and analysis;
- Flexible manufacturing units and associated production lines support the digital automation using sensor technology in manufacturing processes and operations.
- Computerized simulation and analysis of virtual models applying Finite Elements Method, Computational Fluid Dynamics, etc. for engineering projects and model-based design of complex systems, where the models describe the features and behaviour of the system in a real world context;
- Digital twins are virtual representations of production systems that are running on different simulation platforms characterized by the synchronization between the virtual and real system based on sensed data and connected smart devices, mathematical models and real time data collection, integration and processing. Digital twins have the role within I4.0 based manufacturing systems of exploiting different features to forecast and optimize the status and behaviour of the production systems at each life cycle phase in real time. The application of digital twins for modeling and simulation is based on existing

implementation of augmented, mixed, and virtual reality for warehousing and material handling systems. Anylogic software company has demonstrated through case studies the success of delivering the advantages of digital twin based models.

- 3D printing is an additive manufacturing (AM) method for rapid prototyping representing a wide range of structures and complex geometries from a three-dimensional (3D) model data. The method consists of printing layers of materials as entities that are formed on top of each other. 3D printing which involves various techniques, materials, and equipment, has evolved providing the ability to represent and rapid changing or adapting manufacturing processes and supply chain operations. It has been applied in industries, architecture, construction, biomechanical and medicine especially dentistry. The application of 3D printing in some industries was slower and limited despite the advantages, e.g., less waste for developing, designing, and prototyping solutions. Novel applications are emerging because new materials and additive manufacturing methods are continuously being developed. One of the main drivers for this technology of becoming more accessible is due to the expiration of earlier patents, which has provided manufacturers the opportunity to develop new 3D printing devices. Recent developments have reduced the cost of 3D printers and hence extending its applications in industry, research and development.

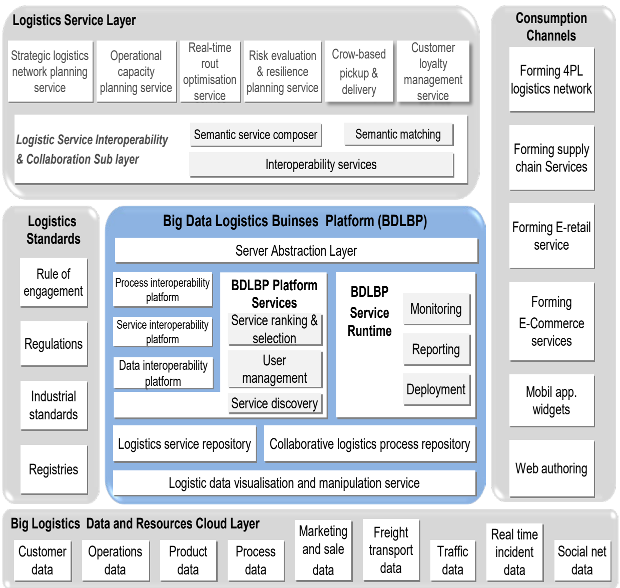

Figure 2. Big Data Logistics Management Cloud Infrastructure and Framework (Neaga et al., 2015)

- Developing big data strategies that incorporate methodologies and methods to collect, process and analysis large amount of structured and unstructured data using predictive and descriptive analytics, data mining, statistical or text analysis and other new methods.
- Developing and deploying cloud services for products and services design, development and logistics management infrastructure. Figure 2 shows a big data driven logistics management cloud infrastructure and framework proposed by Neaga et al., 2015.

The architectural framework big data logistics business platform (BDLBP) is defined as an integration approach and strategy that deliver extensive development of the logistics data processing, visualization and manipulation services, supporting data using, supply chain services and logistics operations process interoperability. The BDLBP includes the services component handling the functions of service ranking and selection, user management and service discovery. The service runtime handles monitoring, reporting and deployment. The BDLBP platform also includes repositories of supply chain services and collaborative logistics operations. The repositories enable sharing and reusing of existing supply chain solutions. The logistics service layer contains various supply chain capability services and a sub-layer for logistics service interoperability and collaboration. The logistics service interoperability and collaboration sub-layer enables a semantic service composer, semantic matching and interoperability services.

Supply chain standards allow transforming textual rule of engagement, rules, and regulations of different countries, and industrial standards into computer understandable information and knowledge. This can then be used to ensure that new forming logistics operations or services complying with existing rules and standards. The consumption channels depict the various ways in which the architecture can be used by external parties.

The platform also includes forming 4PL logistics networks; forming supply chain services; forming e-retail services; and e-commerce services; mobile applications and web components; and web authoring.

4. RESEARCH DESIGN APPROACH

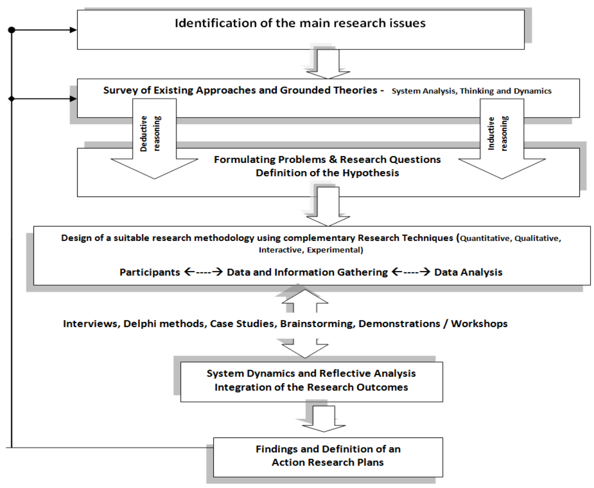

Figure 3. Research Design Approach

The research design approach is presented in figure 3. This is based on the combination between different methodologies such as systematic literature review and desk research as well as empirical investigation. Therefore the methodology is essentially mixed applying a constructivist analysis in the sense that it relies largely on methods such as systematic reviews, surveys (and potentially further interviews) to construct the view of application of I4.0. Other methods used are holistic system thinking, and analysis and systems dynamic alongside empirical studies, correlation, causal comparison and contingency theory.
Figure 3 indicates the research issues and problem identification through exploring the dominant world views (O'Leary, 2005) alongside exploring different perspectives using systematic review, survey analysis and systems thinking. The analysis of the survey is used to draw some conclusions that are compared to similar studies.
The research methodology is firstly performing a systematic critical review of the relevant literature applying content and thematic analysis (Saunders, Lewis and Thornhill, 2012). The diagram of performing systematic review is presented in figure 4.
This research in progress is using presently secondary data analysis of text presented in academic publications, reports and other materials. For achieving the research aim and objectives case studies will be developed (Yin, 2003). The case study research method represents an in-depth inquiry into a topic or phenomenon within its real-world settings. It may refer to an organisation, an association, and processes leading at obtaining insights within the study of the phenomenon in the real world context that support the creation of the new knowledge and theory (Saunders, Lewis and Thornhill, 2012).

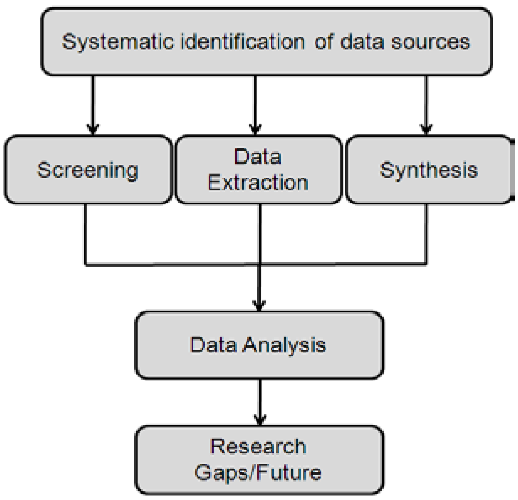

Figure 4. Systematic review process

This approach might lead to an action research that is a methodology that has become increasingly popular and has been developed in companies. In order to be applied in the companies the systems and platform will be developed and prototyping.

A roadmap could be also used in order to predict the future of the application of I4.0 correlated with industrial needs, business profits and skills requirements. An existing roadmap for I4.0 evolution and implementation is presented in figure 5 (Santos et al., 2017)

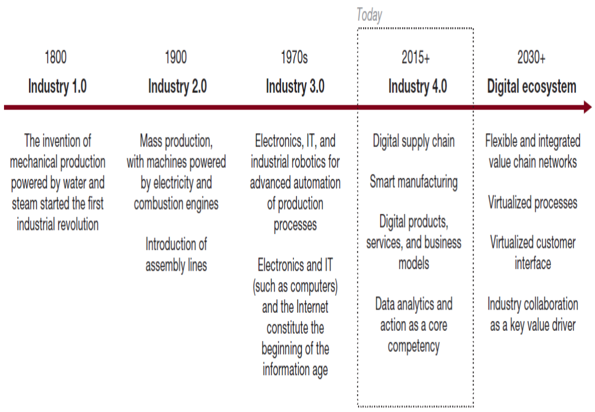

Figure 5. Roadmap of I4.0

5. ACHIEVING THE CIRCULAR ECONOMY

Ellen MacArthur Foundation has provided a definition of the circular economy (CE) as "an industrial economy that is restorative or regenerative by intention and design" (2013:14). CE and sustainable developments driven by the adoption of I4.0 technologies are intensively researched in the academia, and in the industrial projects. The definitions, similarities, and differences between the concepts of CE, and sustainability have been articulated and the complex relation implying the application of I4.0 is presented in figure 6.
Sustainability and circular economy concepts and paradigms 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 in depth the relations between the concepts and have been made explicit the common aspects and differences based on systematic literature reviews, empirical research, and development. CE is an approach and strategy aiming at the sustainable usage of resources and energy (McDowall et al., 2017). It is focused on maximizing the circularity by recycling and reusing of the materials and finding new sources of renewable energy within industrial systems based on the reality that natural resources are limited, and the waste at the end of products lives has retained values that should be reintroduced in the supply chains (Ghisellini et al., 2016).
Therefore the CE is a regenerative system in which input resources and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing the loops of materials, other resources and energy. This supply chain strategy is also defined as closed loop and can be achieved through design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling techniques.

The sustainable development has been interpreted as the balanced integration of economic performance, social inclusiveness, and environmental resilience to the benefit of present 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,b) have recently discussed that the I4.0 technologies have the potential to support environmentally sustainable development and the critical success factors (CSF) of this process are identified through literature-based research and practice. The CSF are considered to have challenges and opportunities to the process of simultaneously implementing I4.0 and sustainable development, especially in manufacturing industry. The approach adopted for sustainable production is related to addressing environmental issues. This approach makes the case for integrating the industrial directions that promise to reshape current trends and patterns of production and consumption: I4.0 and environmentally sustainable production. Big data analytics studies will be developed for insights associated with trends and patternd in sustainable developments.

Lopes Sousa Jabbour et al. (2018b) have argued that I4.0 technologies nevertheless have a huge potential to contribute to the environmentally sustainable production and supply chains practices. A realistic synergy between I4.0 and environmentally sustainable production relies on understanding the role played by critical success factors, which organizations should consider carefully when simultaneously implementing I4.0 and environmentally sustainable manufacturing and associated processes and operations.

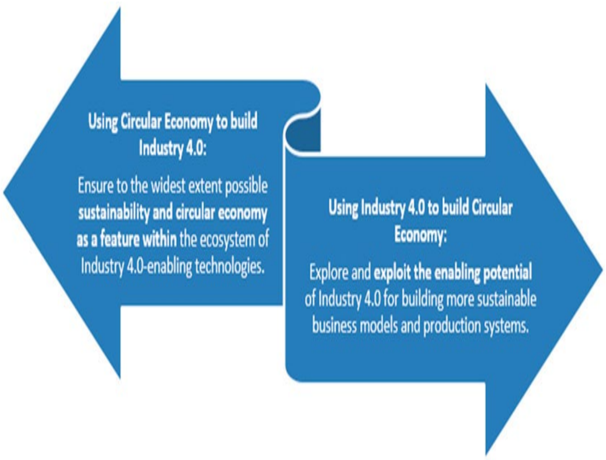

Figure 6. The relation between CE and I4.0

As this is one of the initial approaches to address whether or not I4.0 could synergistically boost environmentally sustainable industries especially manufacturing – with an emphasis on the critical success factors (CSF) that can pose challenges and opportunities to this process leading to an integrative framework containing some research propositions and paradigms. Also in the context of sustainable production companies, Lopes de Sousa Jabbour et al. (2018b) proposed a roadmap to facilitate the application of circular economy principles in organizations and industrial companies within the I4.0 environment aiming at the sustainable use of resources.

6. CONCLUSIONS AND FUTURE WORK

This paper presents a holistic overview and discussion of the I4.0 technologies platforms and systems supporting the sustainable development and the integration of these technologies for enhancing environmentally sustainable industrial production and their supply chains leading at the development of CE. The paper discusses the technology driven innovation supporting the maximization the positive impacts of technologies, namely IoT, and 3D printing, blockchain and digital twins on sustainable development and CE. It also analyzes the relationships between sustainability and the CE concepts and principles, and how these concepts are applied in practice. This research in progress demonstrates that I4.0 technologies can unlock the full potential of environmentally sustainable development and can support the intelligent/smart factories by enabling producing green products, greening the production processes, and their supply chains. It also contributes to the existing literature by comparatively discussing a variety of I4.0 technologies that could underpin the development and implementation of CE strategies, which are useful to the organizations, by including 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 supporting the positive impacts of I4.0 technologies. Also in the future the three pillars of sustainability called triple bottom lines (3BL) and defined as the synergy of Environment – Society - Economy should be added to this study for a multi- and cross-disciplinary applied research.

The future studies will discuss in depth the topics in relation to environmental conservation and protection and climate change, renewable energy and waste management, optimization strategies, financial/banking computer services accessibility and improvement as well as education for the future of work. The increased legitimacy of political decision-making, ecosystem-conscious agriculture food production, protection and conservation of heritage sites and cultural traditions associated with transparency in the production sectors, the promulgation of worker rights and well-being along the sustainable global supply chains, socially responsible business productivity and profitability maximization will be considered.

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